GEORGIA INSTITUTE OF TECHNOLOGY | OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ______

Project No. E-16-662 GTRI/GIT DATE 01/26/84

Project Director: Dr. Ben Zinn School/Lab Aero. Eng.

Sponsor: Gas Research Institute
Chicago, Illinois 60631

Type Agreement: Grant No. 5083-260-0873

Award Period: From 12/1/83 To 12/31/86 (Performance) 3/31/87 (Reports)

Sponsor Amount:

	This Change	Total to Date
Estimated:	$	$ 322,979*
Funded:	$	$ 322,979*

Cost Sharing Amount: $ 32,078 Cost Sharing No: E-16-339

Title: "Pulsating Burners - Controlling Mechanisms and Performance"

ADMINISTRATIVE DATA

OCA Contact John W. Burdette X4820

1) Sponsor Technical Contact:

2) Sponsor Admin/Contractual Matters:
~~Mr. Greg Wojeiechowski~~
Contract Administrator
Gas Research Institute
8600 West Bryn Mawr Avenue
Chicago, Illinois 60631
(312) 399-8100

Defense Priority Rating: N/A

Military Security Classification: N/A
(or) Company/Industrial Proprietary: N/A

RESTRICTIONS

See Attached -- Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with sponsor (GTRI)

COMMENTS:

GRI's support of the work under this grant is conditional upon an annual commitment of funds. Such commitment is the maximum amount Georgia Tech is authorized under this Grant to expend and/or have committed as of the last day of the specified grant period. The "Funding Commitment" is outlined on page 1 of the Grant.

COPIES TO:

Project Director
Research Administrative Network
Research Property Management
Accounting
Procurement/EES Supply Services
Research Security Services
Reports Coordinator (OCA)
Research Communications (2)
GTRI
Library
Project File
Other ______

GEORGIA INSTITUTE OF TECHNOLOGY **OFFICE OF CONTRACT ADMINISTRATION**

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 10-1-87

Project No. E-16-662 School/~~Lab~~ AE

Includes Subproject No.(s) N/A

Project Director(s) Dr. Ben Zinn GTRC / ~~GIT~~

Sponsor Gas Research Institute

Title "Pulsating Burners - Controlling Mechanisms and Performance"

Effective Completion Date: 12-31-86 (Performance) 4-30-87 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [x] Final Invoice or Final Fiscal Report
- [ ] Closing Documents
- [x] Final Report of Inventions Questionnaire sent to P.I.
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other

Continues Project No. Continued by Project No.

COPIES TO:

Project Director
Research Administrative Network
Research Property Management
Accounting
Procurement/GTRI Supply Services
Research Security Services
[redacted]
Legal Services

Library
GTRC
Research Communications (2)
Project File
Other

FORM OCA 69.285

E-16-66

GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF AEROSPACE ENGINEERING
ATLANTA, GEORGIA 30332
Telephone 404-894-3033/3000
Telex: SY2507 GTRI OCA ATL

Ben T. Zinn
Regents Professor
Daniel Guggenheim
School of Aeronautics

March 12, 1984

Mr. James A. Kezerle
Gas Research Institute
8600 West Bryn Mawr Avenue
Chicago, Illinois 60631

Subject: Progress report for the period December 1, 1983 through February 29, 1984 for work conducted under Grant 5083-260-0873.

Der Mr. Kezerle:

During the initial phase of this report period the research activities to be performed under this program were reviewed with the objective of developing a research program which will complement the one conducted at Battele Research Institute, also under GRI support. As part of this effort, representatives of the Georgia Tech and Battele groups met at the A.G.A. Laboratories in Cleveland, Ohio with Mr. Kezerle to discuss the research problems which need to be addressed under these research programs, the tasks to be undertaken by each group and future cooperation between these groups. In addition, the visit to the A.G.A. Laboratories provided the participants with an opportunity to observe first hand the testing procedures of various pulsating combustors.

One output of the above mentioned planning efforts, was the development of test program whose initial objective will be the determination of the effects of combustion chamber geometry on combustor performance. The ten combustor configurations which will be investigated are shown in Fig. 1. These ten configurations represent variations from the basic combustor design provided by A.G.A., which will be referred to as the reference combustor.

An examination of Fig. 1 reveals that the chosen combustor configurations will permit the determination of the effects of varying L/d upon the combustor performance while keeping the combustor volume, combustor length and combustor diameter constant. In addition, these tests will determine the effect of changing the combustion chamber volume while keeping L/d constant, upon combustor performance.

During the report period, the design and fabrication of the basic components for the reference (A.G.A.) combustor have been completed and the assembly of the experimental set-up has been initiated. Two of the ten combustion chamber configurations required for the initial test program have been fabricated. Testing of the reference combustor configuration will begin shortly after the receipt of the components for the ignition system and the gas metering and control system, which is expected within the next few weeks.

Considerable time has also been expended on the planning of the measurements which will be performed during a given test. The objectives of these measurements will be to determine the combustor performance and, hopefully, the driving (of the oscillations) provided by the combustion process. The latter will have to be determined in concert with a realistic model of the combustor. Factors which will be considered in the evaluation of the combustor performance will include the stability of the operation, the combustion and thermal efficiencies of the device, the spatial and time dependences of the pressure oscillations, the spatial and time characteristics of the temperature field, NO_x and CO formation and so on. These determinations will require dynamic pressure and temperature measurements throughout the combustor, exhaust flow composition measurements and air and gas flow rate measurements. The development of the required measurement systems is in progress.

Considerable time was spent on the planning and design of the optical diagnostics which will be used later on in this program. These activities included:

- Selection of components for an LDV system to obtain maximum flexibility in pulsed combustor studies. The investigated problems included choice of laser, choice of computer for data reduction and storage and choice of a suitable table. All purchase requests have gone out for bids. With the exception of the one for the computer system, all bids have been received and orders placed.

- The Schlieren and shadowgraphy system for flow visualization has been designed and the components ordered. Bids for all major items have been received and orders placed.

- The optical tables for the LDV and Schlieren systems have been designed and materials ordered.

- Various possible particle seeding systems for the LDV, streamline and mixing visualization are being considered.

- Optical systems for laser sheet formation and laser sweep mechanisms, required for the flow visualization studies, are being designed.

Finally, a low level effort aimed at the development of an analytical model capable of describing the performance of the investigated pulsating combustor has been initiated. Also, this group participated in GRI's Research Meeting at Sandia, Livermore, California. This participation included a presentation which described the present program.

Sincerely,

B. T. Zinn
Principal Investigator

BTA/jj

cc: Mr. B. R. Daniel and Dr. J. Jagoda

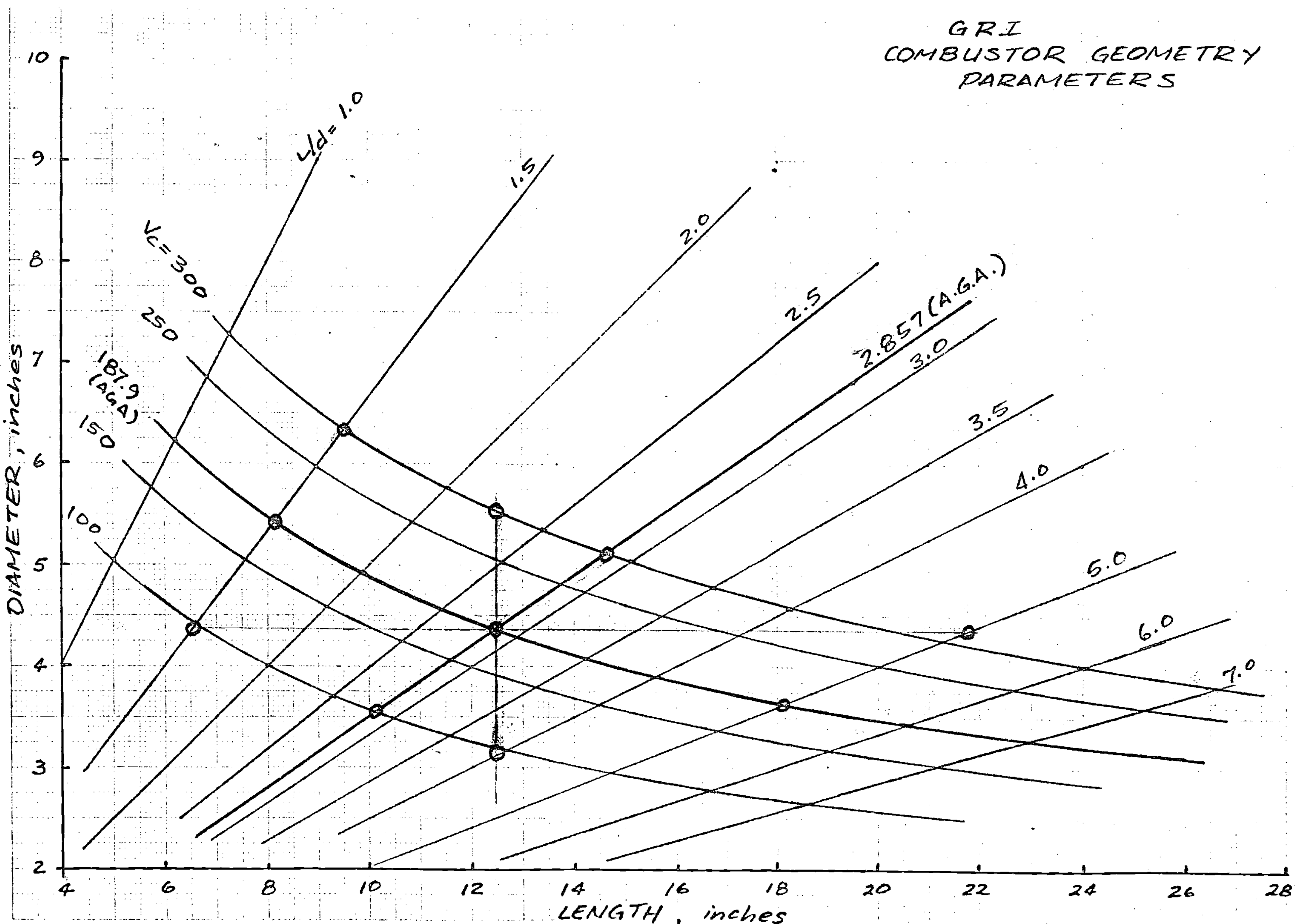


Figure 1. Proposed Combustor Diameters and Lengths (shown in red)

E-10-660

Pulsating Burners - Controlling Mechanisms and Performance

Quarterly Report
December '84 - February '85

Prepared by

B. T. Zinn, B. R. Daniel and J. I. Jagoda

School of Aerospace Engineering
Georgia Institute of Technology

For

Gas Research Institute
Grant No. 5083-260-0873

GRI Project Manager
James A. Kezerle
Combustion

March 26, 1985

RESEARCH SUMMARY

Title	Pulsating Burners - Controlling Mechanisms and Performance
Contractor	Georgia Tech Research Institute
Contract Number	GRI Grant 5083-260-0873
Principal Investigators	B. T. Zinn, B. R. Daniel and J. I. Jagoda
Objective	The objective of this study is to gain an understanding of the fundamental processes, such as mixing and cycle to cycle reignition, which control the operation of gas fired pulsed combustors. An analytical model is to be developed which will provide a rational procedure for the design and scaling of these burners.
Technical Perspective	In spite of the fact that gas fired pulsed combustors for home heating have now been on the market for a number of years, little is known about the physical and chemical processes which control the operation of these devices. Of particular interest are the mixing of fuel and air, cycle to cycle ignition and the nature of the flame propagation in the burner. Such information is necessary for improving the operational characteristics of existing pulsating combustors and for guidance in the development of new burners for increased capacity or novel applications. Furthermore, the acquired insight will be used to guide the development of a theoretical model for predicting the behavior of pulsating combustors. The availability of such a model would permit the replacement of the costly empirical trial and error methods used to date for the design and scaling of pulsed combustors by a more rational approach.

Technical Approach

As a first step, a parametric study is being carried out using steel combustors in order to determine the influence of the combustor geometry on its performance and efficiency. Selected burners have and will be fabricated in pyrex and quartz and their flow field investigated using high speed cinematography Schlieren/shadowgraphy, stream line and mixing visualizations as well as laser Doppler velocimetry (LDV). Lastly, C-H and C-C spectroscopy is being used in the determination of the timing, location and rate of heat release during the combustion cycle. A linear and, if necessary, a non-linear theoretical model of the combustor is being developed to provide a basis for future pulsating combustor design and scaling.

Program Plan

The program is divided into three major tasks as outlined below:

Task I	-	Experimental Investigation	
	A	Performance Evaluation	
	B	Flow Visualization	a) streamline visualization
			b) shadow/schlieren
	C	Mixing Visualization	
	D	LDV	
	E	C-H & C-C Spectroscopy	
Task II	-	Analytical Study	
Task III	-	Reporting	

Results

To date a test matrix for the parametric study of the performance of gas fired pulsating combustors (GFPC) has been developed. All components required to assemble the 10 combustors in the test matrix were fabricated. Pyrex end plates for the mixing and combustion chambers which can be used for all 10 combustors have also been obtained and the hardward required to fit them to the combustors has been fabricated. A large decoupling chamber has been added upstream of the air valve which permits the measurement of the mean air flow rate. An all pyrex combustor for optical diagnostics has been developed and tested. Early problems with explosions in the glass combustor during ignition have been solved. All these combustors are operational and have been extensively used. An exhaust gas analysis train to determine the combustion products composition and, thus, the combustion efficiencies has been designed and constructed. The individual detectors have been calibrated and testing has begun. A scheme for determining combustion efficiencies from the analysis of the exhaust gases has been developed. The software for acquiring and analyzing the temperatures, pressures, exhaust gas compositions and combustion efficiencies of the combustor has been written for an HP series computer and successfully tested. A two component LDV system and the computer for its data acquisition have been set up and has been tested. An optical set-up for measuring C-C and C-H radiation and a high speed Schlieren and shadowgraph system have been placed in operation. An expanded laser beam system for particle tracking and mixing visualizations has been set up and tested. A similar set-up in which a focused beam is rapidly swept through the test section has been designed and is currently being set up.

Initial performance tests have been carried out on all ten combustors in the test matrix. All ten combustors operated satisfactorily although the large volume combustors were somewhat more difficult to ignite. Analysis of the data, using a simplified model, showed that for the tested combustors the combustor volume is the parameter which controls the frequency of pulsations. This analysis also showed that the developed combustors operate as Helmholtz resonators. An eleventh combustor was designed and constructed. For this unit the diameters of the mixing and combustion chambers were the same, thus effectively eliminating the step between mixing and combustion chamber. This combustor ran well and exhibited the same accoustic characteristics as a combustor with step and equal volume suggesting that the step does not influence the combustion process significantly.

Visual observation in the all pyrex combustor showed that for this configuration most of the combustion actually takes place in the "mixing" chamber. High speed Schlieren and shadowgrams were used to visualize the incoming fuel and air jets, their mixing and combustion. Low sensitivity Schlieren was used to separate the Schlieren markings due to hot and cold gas interfaces from those due to flame fronts. C-H and C-C radiation from the entire combustor were measured for relatively lean, relatively rich and optimum combustion conditions. The latter correspond to those used in the visualization studies. These measurements strongly suggest that the combustion does not cease at any time during a cycle of operation. For a fixed fuel input, the magnitude of the radiation fluctuations decrease as the air inflow is reduced (i.e., the fuel/air ratio increases). Corresponding changes in the pressure fluctuations appeared considerably smaller. Comparison of the Schlieren and radiation results indicated that there is a pronounced increase in reaction rate when the fuel and air jets first mix.

INTRODUCTION

The objective of this study is to gain insight into the fundamental processes responsible for the operation of gas fired pulsed combustors and to develop an analytical model capable of predicting the performance characteristics of new pulsed combustor designs. Furthermore, the model* will consider the effect of scaling upon combustor performance. To this end, the effects of a number of geometrical combustor parameters such as L/D ration combustor volume and exhaust pipe length and diameter upon the combustor performance are under investigation. Also, the interactions between the pulsed flow field and combustion processes are being studied. Special emphasis is placed on determining the source and location of the cyclic ignition and following the flame spread in the combustor. The streamlines in the flowfield and the mixing of fuel and air are being visualized and recorded. Velocities and species concentrations are measured using LDV and Raman. An analytical model is being developed which will predict the performance of combustors having different geometries and scales. The insights gained from the above experiments will be used in the development of the model which will, in turn be tested against further experimental data. It is, thus, anticipated that this study will enable the industry to abandon the hereto used empirical approach in the design and development of pulsed combustors in favor of a rational design procedure based upon dependable model predictions.

PROGRAM PLAN

The program is divided into three major tasks as outlined below:

Task I - Experimental Investigation

A. Performance Evaluation. The performance of a number of combustors of different geometries (i.e., different L/D, volumes, tail pipe lengths, etc.) is being investigated using temperature, pressure and combustion efficiency measurements. For each configuration, the performance is evaluated over a range of air/fuel ratios and fuel loadings.

B. Flow Visualization. Stream lines are being investigated by recording the tracks of seed particles moving through a laser light sheet. This process is repeated with the laser sheet at different combustor locations. Refractive index gradients caused by the flame front or by pockets of hot and cold gases are visualized using Schlieren and shadowgraphy.

C. Mixing Visualization. Mixing patterns are being recorded photographically by heavily seeding either the fuel or the air and illuminating the transparent combustor using a laser light sheet. Again, the visualization is repeated with the laser sheet at different combustor locations.

D. LDV. Although the bulk of the laser Doppler velocimetry measurements will be carried out in the second and third years, the system has been set up during the first year. The data acquisition system previously developed is being modified to permit ensemble averaging over a number of cycles and the problem of beam displacement due to the cylindrical walls is being addressed.

E. C-H & C-C Spectroscopy. Although this part of the study was originally reserved for the second and third years, some measurements were already carried out and significant results obtained. Radiation from the combustor is passed through the respective filters and its intensity measured using a photomultiplier. The radiation measurements are then related to combustion intensities.

Task II - Analytical Study

A theoretical model which describes the performance of the investigated combustors is being developed. The model incorporates the findings of the experimental phases of the program. The model is linear and investigates the possible range of operating conditions of the burners. Should this not result in satisfactory agreement with the experimental data, the non-linearities of the problem will be incorporated in the model.

Task III - Reporting

As per contract agreement.

TECHNICAL PROGRESS AND RESULTS

During the early part of this reporting period (December '84 - February '85) the C-C and C-H radiation measurements were correlated with the high speed shadowgraph movies. Both results were reported last December in the annual report. As explained in that report the C-C and C-H radiation are indicative of the level of chemical reaction occurring in the combustor, although at this time not enough is known about the reaction kinetics of the oxidation of methane to state definitively that the presence of excited C-C or C-H radicals is indicative of the existence of a traditional "flame". Both C-C and C-H radiation fluctuations were found to be in phase with each other and slightly leading the pressure oscillations indicating that Rayleigh's criterion is obeyed in the combustor under investigation. When the radiation fluctuations were correlated with the mixing pattern of the fuel and air jets recorded by the high speed shadowgraphy, it was noted that in each cycle the increase in the detected levels of excited C-C and C-H radicals coincides with the instant at which the air jet first impinges on the fuel jet. Assuming for the moment (unless contrary evidence is provided by ongoing methane kinetics research) that these radiating signals provide a measure of the methane reaction rate this observation indicates that the cycle to cycle reignition of the new reactants coincides with the instant at which the new fuel and air first mix. Similar observations were made using the low sensitivity, Schlieren set up as described in the annual report. The ignition source for the new reactants may be expected to consist of entrained radicals left over in the mixing chamber from the previous cycle. In this connection it should be pointed out that it is well known that under certain conditions the entrainment rates of pulsating jets are considerably higher than those of steady jets.

Also during this reporting period, a large decoupling chamber was attached to the upstream side of the air flapper valve of the steel combustor. The inlet to the decoupling chamber was connected via a rotameter type flow meter to a pressure regulator fitted to a pressurized air supply. The chamber was equipped with a manometer and a rapture disk for safety. This arrangement made it possible to measure the mean air flow rate while maintaining the upstream side of the air flapper valve at atmospheric pressure. A flow meter was also incorporated in the fuel line. It is, thus, now possible to monitor both fuel and air flow rates during the operation of the combustor.

A heated combustion product sample probe was designed and fabricated. It is used to pass gas samples from the combustor tail pipe to the sample train. The CO_2, CO, O_2 and NO_x analyzers which are included in the sample train have been calibrated and the entire system has been throughly checked out. Measurements of the combustion efficiency of the various combustors have been started.

The components for one more combustor was fabricated. In this combustor the diameter of the combustion chamber was equal to that of the mixing chamber thus effectively eliminating the step between the mixing and combustion chambers. Other workers have previously deemed this step to be essential for flame stabilization through the trapping of radicals in its recirculation zone. Tests were carried out which have shown the stepless combustor to operate perfectly although the spark from the spark plug had to be left on for about 10 seconds. After this "warm up period", which was not necessary in the combustors with steps, the combustor ran without the need for an external ignition source. The frequency and the dB level of the combustion process in this device were found to be equal to those measured in a combustor of equal volume with step . These results suggest that the step does not play an important role in sustaining the pulsating combustion process. The reasons for the longer (i.e. 10 sec) warm up time in the stepless combustor are, at present, not understood and will be further investigated.

Finally, a light sheet for streamline visualizations was generated by expanding the beam from a 5 watt argon ion laser using a cylindrical lens as reported in the annual report. Various particles of different sizes and materials were tested as tracers. Best results were obtained using relatively light particles of approximately 50 micron diameter which are intended for use in an electric eraser. However, because of the reduced intensity of the expanded beam the recorded particle tracks were not as clear as expected. The unexpanded beam, on the other hand, contained sufficient power to yield a clear particle track. Various optical systems were, therefore, considered which would permit one to sweep the unexpanded beam rapidly through the test section. A number of such sweeps would be required while the shutter of the recording camera is open. Different systems have been considered and some are presently being tested. Mixing can also be visualized using this optical set up if one flow (either gas or air) is heavily seeded using submicron TiO_2 particles. However, because of the mixing of the reactants with the products from the previous cycle, clear patterns can only be obtained if seed particle injection can be limited to the duration of one cycle only. Various techniques including the use of fluidic valves are presently under investigation for achieving this one cycle injection.

PLANNED WORK

During the next reporting period (March - May 1985) the efficiency, performance and NO_x emission measurements on the various combustors will be continued. Each combustor will be tested under conditions of different fuel/air ratios. The optical system for visualizing stream lines and mixing patterns will be modified to permit high frequency sweeping of the laser beam through the test region. The possible use of fluidic valves to inject tracer particles into the flow during one cycle only will be investigated. An additional combustor will be designed and fabricated. This combustor will contain flat windows in the curved parts of both the mixing and combustion chambers as well as flat end walls made of pyrex. This will facilitate the simultaneous recording of high speed shadowgrams in both the end-on and the side-on directions, which is necessary in order to completely analyze the complex 3-D flows present in the pulsed combustor. The flat windows will also improve the velocity measurements using the 2-D LDV. Finally, the modeling efforts on the pulsed combustor will continue.

E-16-662

Pulsating Burners - Controlling Mechanisms and Performance

Quarterly Report

March '85 - May '85

Prepared by

B. T. Zinn, B. R. Daniel and J. I. Jagoda

School of Aerospace Engineering

Georgia Institute of Technology

For

Gas Research Institute

Grant No. 5083-260-0873

GRI Project Manager

James A. Kezerle

Combustion

June 15, 1985

GRI DISCLAIMER

RESEARCH SUMMARY

Title	Pulsating Burners - Controlling Mechanisms and Performance
Contractor	Georgia Tech Research Institute
Contract Number	GRI Grant 5083-260-0873
Principal Investigators	B. T. Zinn, B. R. Daniel and J. I. Jagoda
Objective	The objective of this study is to gain an understanding of the fundamental processes, such as mixing and cycle to cycle reignition, which control the operation of gas fired pulsed combustors. An analytical model is to be developed which will provide a rational procedure for the design and scaling of these burners.
Technical Perspective	In spite of the fact that gas fired pulsed combustors for home heating have now been on the market for a number of years, little is known about the physical and chemical processes which control the operation of these devices. Of particular interest are the mixing of fuel and air, cycle to cycle ignition and the nature of the flame propagation in the burner. Such information is necessary for improving the operational characteristics of existing pulsating combustors and for guidance in the development of new burners for increased capacity or novel applications. Furthermore, the acquired insight will be used to guide the development of a theoretical model for predicting the behavior of pulsating combustors. The availability of such a model would permit the replacement of the costly empirical trial and error methods used to date for the design and scaling of pulsed combustors by a more rational approach.

Technical Approach

As a first step, a parametric study is being carried out using steel combustors in order to determine the influence of the combustor geometry on its performance and efficiency. Selected burners have and will be fabricated in pyrex and quartz and their flow field investigated using high speed cinematography Schlieren/shadowgraphy, stream line and mixing visualizations as well as laser Doppler velocimetry (LDV). Lastly, C-H and C-C spectroscopy is being used in the determination of the timing, location and rate of heat release during the combustion cycle. A linear and, if necessary, a non-linear theoretical model of the combustor is being developed to provide a basis for future pulsating combustor design and scaling.

Program Plan

The program is divided into three major tasks as outlined below:

Task I - Experimental Investigation
- A Performance Evaluation
- B Flow Visualization a) streamline visualization
  b) shadow/schlieren
- C Mixing Visualization
- D LDV
- E C-H & C-C Spectroscopy

Task II - Analytical Study

Task III - Reporting

Results

To date a test matrix for the parametric study of the performance of gas fired pulsating combustors (GFPC) has been developed. All components required to assemble the 10 combustors in the test matrix were fabricated. Pyrex end plates for the mixing and combustion chambers which can be used for all 10 combustors have also been obtained and the hardward required to fit them to the combustors has been fabricated. A large decoupling chamber has been added upstream of the air valve which permits the measurement of the mean air flow rate. An all pyrex combustor for optical diagnostics has been developed and tested. Early problems with explosions in the glass combustor during ignition have been solved. All these combustors are operational and have been extensively used. An exhaust gas analysis train to determine the combustion products composition and, thus, the combustion efficiencies has been designed and constructed. The individual detectors have been calibrated and testing has begun. A scheme for determining combustion efficiencies from the analysis of the exhaust gases has been developed. The software for acquiring and analyzing the temperatures, pressures, exhaust gas compositions and combustion efficiencies of the combustor has been written for an HP series computer and successfully tested. A two component LDV system and the computer for its data acquisition have been set up and has been tested. An optical set-up for measuring C-C and C-H radiation and a high speed Schlieren and shadowgraph system have been placed in operation. An expanded laser beam system for particle tracking and mixing visualizations has been set up and tested. A similar set-up in which a focused beam is rapidly swept through the test section has been designed and is currently being set up.

Initial performance tests have been carried out on all ten combustors in the test matrix. All ten combustors operated satisfactorily although the large volume combustors were somewhat more difficult to ignite. Analysis of the data, using a simplified model, showed that for the tested combustors the combustor volume is the parameter which controls the frequency of pulsations. This analysis also showed that the developed combustors operate as Helmholtz resonators. An eleventh combustor was designed and constructed. For this unit the diameters of the mixing and combustion chambers were the same, thus effectively eliminating the step between mixing and combustion chamber. This combustor ran well and exhibited the same accoustic characteristics as a combustor with a step and equal volume suggesting that the step does not influence the combustion process significantly.

Visual observation in the all pyrex combustor showed that for this configuration most of the combustion actually takes place in the "mixing" chamber. High speed Schlieren and shadowgrams were used to visualize the incoming fuel and air jets, their mixing and combustion. Low sensitivity Schlieren was used to separate the Schlieren markings due to hot and cold gas interfaces from those due to flame fronts. C-H and C-C radiation from the entire combustor were measured for relatively lean, relatively rich and optimum combustion conditions. The latter correspond to those used in the visualization studies. These measurements strongly suggest that the combustion does not cease at any time during a cycle of operation. For a fixed fuel input, the magnitude of the radiation fluctuations decrease as the air inflow is reduced (i.e., the fuel/air ratio increases). Corresponding changes in the pressure fluctuations appeared considerably smaller. Comparison of the Schlieren and radiation results indicated that there is a pronounced increase in reaction rate when the fuel and air jets first mix.

A series of tests aimed at determining the performance of the developed combustors under various operating conditions has begun. First, the performance of the AGA combustor was investigated. During these tests temperatures and pressures were measured at various locations near the fuel and air flapper valves, in the mixing chamber, the combustion chamber and the exhaust pipe. Fuel and air flow rates were measured upstream of the flapper valves. At the same time, the concentration of CO, CO_2, O_2 and NO_x were measured in the exhaust gases. From these values the combustion efficiencies and the fuel equivalence ratios were calculated. The range of operation of the combustor was established by varying the air flapper valve settings. The combustor operated well at fuel equivalence ratios between .85 and .55. Optimum performance was achieved at a fuel equivalence ratio of .62. The data for this condition were reduced in detail. The frequency of oscillation was 38 Hertz and the dB level 169.5. The maximum temperature in the mixing chamber was nearly 1000°C, a short distance upstream of the combustor.This temperature increases to a higher value at the entrance of the combustor, after which it drops until it reaches 300°C just before the decoupling chamber. The combustion efficiency was determined to be above 99% with CO levels of about 50 ppm and NO_x levels of 25ppm. Similar tests were carried out for different fuel air ratios in the same combustor. These results are still being analyzed and will be reported in the next progress report. However, it was noted that combustion efficiencies, dB levels and NO_x concentrations do not change significantly until the rich and lean limits of operation of the combustor are reached.

INTRODUCTION

The objective of this study is to gain insight into the fundamental processes responsible for the operation of gas fired pulsed combustors and to develop an analytical model capable of predicting the performance characteristics of new pulsed combustor designs. Furthermore, the model will consider the effect of scaling upon combustor performance. To this end, the effects of a number of geometrical combustor parameters such as L/D ratios, combustor volume and exhaust pipe length and diameter upon the combustor performance are under investigation. Measurements include the determination of temperature and pressure distributions, combustion efficiencies, NO_x levels in the exhaust gases and fuel air ratios for the different combustion under various operating conditions. Also, the interactions between the pulsed flow field and combustion processes are being studied. Special emphasis is placed on determining the source and location of the cyclic ignition and following the flame spread in the combustor. The streamlines in the flowfield and the mixing of fuel and air are being visualized and recorded. Velocities are measured using LDV. An analytical model is being developed which will predict the performance of combustors having different geometries and scales. The insights gained from the above experiments will be used in the development of the model which will, in turn, be tested against further experimental data. It is, thus, anticipated that this study will enable the industry to abandon the hereto used empirical approach in the design and development of pulsed combustors in favor of a rational design procedure based upon dependable model predictions.

PROGRAM PLAN

The program is divided into three major tasks as outlined below:

Task I - Experimental Investigation

A. Performance Evaluation. The performance of a number of combustors of different geometries (i.e., different L/D, volumes, tail pipe lengths, etc.) is being investigated using temperature, pressure and combustion efficiency measurements. For each configuration, the performance is evaluated over a range of air/fuel ratios and fuel loadings.

B. Flow Visualization. Stream lines are being investigated by recording the tracks of seed particles moving through a laser light sheet. This process is repeated with the laser sheet at different combustor locations. Refractive index gradients caused by the flame front or by pockets of hot and cold gases are visualized using Schlieren and shadowgraphy.

C. Mixing Visualization. Mixing patterns are being recorded photographically by heavily seeding either the fuel or the air and illuminating the transparent combustor using a laser light sheet. Again, the visualization is repeated with the laser sheet at different combustor locations.

D. LDV. Although the bulk of the laser Doppler velocimetry measurements will be carried out in the second and third years, the system has been set up during the first year. The data acquisition system previously developed is being modified to permit ensemble averaging over a number of cycles. An additional combustor with flat walls is being fabricated in order to avoid the problem of beam displacement due to the cylindrical walls.

E. C-H & C-C Spectroscopy. Although this part of the study was originally reserved for the second and third years, some measurements were already carried out and significant results obtained. Radiation from the combustor is passed through the respective filters and its intensity measured using a photomultiplier. The radiation measurements are then related to combustion intensities.

Task II - Analytical Study

A theoretical model which describes the performance of the investigated combustors is being developed. The model incorporates the findings of the experimental phases of the program. The model is linear and investigates the possible range of operating conditions of the burners. Should this not result in satisfactory agreement with the experimental data, the non-linearities of the problem will be incorporated in the model.

Task III - Reporting

As per contract agreement.

TECHNICAL PROGRESS AND RESULTS

During the past reporting period (March '85 - May '85) detailed performance and efficiency tests were started. Extensive measurements were carried out on the "AGA" combustor. For these studies, each combustor is tested in two different instrumentation configurations. The first, in which temperatures and efficiencies are determined, is shown in Fig. 1. Temperatures are measured and recorded in 9 locations; one in the mixing chamber, three in the combustion chamber and five along the exhaust pipe. At present, all temperatures are measured along the center line of the combustor although provisions have been made to carry out temperature traverses. The temperatures are measured with chromel alumel thermocouples whose signal is amplified using NEFF amplifiers and digitized in a Preston 16 channel A/D converter before being stored in an HP computer. These thermocouples are shielded and, therefore, have sufficient mass to respond only to mean temperatures and not to their cyclic fluctuations. Unshielded fine wire thermocouples can and will be used to investigate temperature fluctuations, but it must be born in mind that a lag and a "clipping" of temperature maxima and minima is introduced by the thermal mass of the couple.

While measuring these temperatures, samples of the exhaust gases are continuously being extracted using a sampling probe placed in the exhaust pipe, approximately one third of the distance of the exhaust pipe length from the combustion chamber. The sample is carried via a heated sample line through a soot retaining filter to a gas sampling train. There it is dried and passed through a series of analyzers whch measure the concentrations of carbon dioxide, carbon monoxide, oxygen and NO_x. A gas chromatograph is currently being added to the sampling train to monitor unburnt hydrocarbons, although the high combustion efficiencies determined for the pulse combustors make the presence of significant quantities of unburnt fuel extremely unlikely, except perhaps near the combustors' limits of operation. The outputs from the gas analyzers are connected to an HP computer via the A/D converter.

In addition to the temperatures and exhaust gas analysis the pressure in the center of the combustion chamber is being monitored for reference as shown in Fig. 1. During each test, the temperature, exhaust gas concentrations and dB level in the combustor are recorded at half second intervals, flashed on the terminal screen and written onto a Winchester disc. In addition, the combustion efficiency and the fraction of excess oxygen or the fuel equivalence ratios are calculated and stored using software developed during an earlier reporting period. In the currently used program soot and unburnt hydrocarbons as well as the humidity of the incoming air are neglected. No soot has been observed in the exhaust flow and the humidity of the combustion air is, nevertheless. monitored.

In the second configuration the thermocouples were replaced by pressure transducers as shown in Fig. 2. These transducers are Kissler microphones. Since they are highly sensitive to heat, they are mounted on steel extension tubes which are connected to "infinite" plastic tubes, to avoid the setting up of standing waves in the extension tubes, (and obtain a flat frequency response), as shown in Fig. 3. Pressures are measured in twelve locations (Fig. 2); one each in front of and behind the air and fuel flapper valves, one in the mixing chamber, three along the axial direction of the combustion chamber, one at the center of the combustion chamber at right angle to the other three (to confirm axial symmetry) and three along the exhaust pipe. The outputs from the pressure transducers are each passed through an amplifier. The signals are then passed to true RMS meters whose outputs are connected via the A/D converter to the computer where they are converted to dB levels. Alternatively they are directly recorded using a tape recorder or via the A/D converter by the computer at a high data rate. This permits one to establish the time histories of the pressure signals.

The fuel flow rate was monitored using a rotameter type flow meter placed in the fuel line. The large decoupling chamber described in the last progress report was fitted to the upstream side of the air flapper valve. This permits the mean air flow rate to be measured using a rotameter type flow meter while maintaining the upstream side of the air flapper at atmospheric pressure. This air flow rate can also be determined from the fuel flow rate and the fuel equivalence ratio calculated using the measured exhaust gas compositions. The air flow rates determined in these two ways have been compared and were found to agree to within better than two percent.

Extensive tests were carried out on the # 1 (AGA) combustor. This combustor was tested with different air flapper valve settings. Satisfactory operation was achieved with settings between .0088" and .015". Tests were conducted with flapper setting of .0088", .009", .010", .011", .012" and .015". Tests with a flapper setting of .016", .017" and .018" with the spark plug left on throughout the run were also made. In addition, the tests with settings of .009", .012" and .016" were repeated without the decoupling chamber upstream of the air flapper valve in order to determine its effect on the combustor performance.

Results obtained from the run with air flapper setting of .012" with the air line decoupler in place are presented in this report. This corresponds to 61% excess air or a fuel equivalence ratio of .62. This setting appears to result in optimum combustor performance if the upstream gas pressure is set to 6" of water. Fig. 4 shows the dB level variation with time during a three minute run. The starting transient after firing up the combustor only lasts for a few seconds after which the dB reading levels off at a mean dB level of 168.2. The corresponding mean temperatures in the mixing and combustion chamber are shown in Fig. 5. These temperatures reach a steady level approximately 15 seconds after the combustor is turned on. After this these temperatures remain constant until the run is completed. The temperatures in the exhaust pipe (Fig. 6) increase rapidly during the initial transient and continue to increase at a low rate throughout the duration of the test. This behavior becomes more apparent as one moves down the tailpipe, indicating that as one moves away from the combustor it takes longer to achieve thermal equilibrium. The measured temperatures suggest that combustion starts in the mixing chamber and extends into the front part of the combustion chamber where the temperature is still rising. By the middle of the combustion chamber the temperature begins to fall indicating that combustion has probably been completed. The temperature continues to drop in the downstream direction except near the entrance into the exhaust pipe where the hot products enter the small diameter exhaust pipe.

The concentration of CO, CO_2, O_2 and NO_x in the exhaust gas are shown in Figs. 7, 8, 9 and 10, respectively. The combustion efficiencies calculated from these concentrations are shown in Fig. 11. The CO level in the exhaust (Fig. 7) rises, after a small delay, to a peak and then drops to a constant level of 45 ppm. This is near the lower limit of the CO detector which explains the fluctuations in the signal. The delay at the beginning of the test is caused by the finite time required for the sample gases to pass through the sample line and the relatively slow response of the detecter. The CO concentration peak which appears of 15 seconds is, therefore, due to the ignition process. This behavior is also shown in the other exhaust gas concentration plots and, therefore, in the efficiency figure. The CO_2 level (Fig. 8), after the delay mentioned above, rises smoothly to a value of 7% where it levels off. The O_2 concentration (Fig. 9) drops to a value of 6% during ignition and then rises to level off at about 8.5%. The NO_x levels (Fig. 10) rise sharply, at first, until they reach a level of, approximately, 20 ppm after 45 sec. After this they continue to increase slightly with time. The reason for this is not clear at this point, since the temperature in the region of highest temperature near the mixing chamber, where most of the NO_x may be expected to be produced remains constant after the first 15 seconds of operation. Tests with longer run times are currently being carried out to determine when the NO_x level and the temperatures at the end of the exhaust pipe reach a steady level. Finally, the combustion efficiency, shown in Fig. 11, while unsteady during and immediately after ignition, levels off at an average value of 99.4%.

Tests have also been carried out in this combustor at other air valve settings and, thus, different fuel equivalence ratios with and without the air decoupling chamber in place. Their results are currently under evaluation. Some trends have, however, already been noted. For the standard fuel flapper valve setting and a fuel line pressure of 6" of water the combustor can be operated with an air flapper valve setting between .0088" and .015". This corresponds to excess air values between 17% and 83% or a fuel equivalence ratio of .85 to .55. These limits can, however, be considerably extended if the spark plug ignition is kept on. Under normal operating conditions the combustor performance does not vary much for fuel equivalence ratios between .85 and .55. For example, the combustion efficiency varies only between 99.4% at its optimum and 98.4% as one approaches the limiting conditions of fuel equivalence ratio. However, as the operating limit is approached, the combustor performance becomes very strongly dependent upon the precise setting of the air valve. This dependence is so critical that it is hard to reset the air valve position in order to achieve repeatable exhaust gas measurements even though the flapper vlave gap can be set to within a fraction of a thousands of an inch. Finally, during all runs very low NO_x levels of between 15 and 35 ppm were observed.

The development of an analytical model has continued during the reporting period.

PLANNED WORK

During the next reporting period (June - August 1985) the remaining data for the AGA combustor will be analyzed. The tests will be extended to include the other combustors and the results will be related to changes in geometry. Particular attention will be paid to the combustion efficiency, the NO_x concentration in the exhaust and the pressure changes across the flapper valves. Simultaneously, the stream line and mixing visualizations will continue. Furthermore, a new combustor will be fabricated which will have flat side glass windows as well as flat end walls made of pyrex. This will facilitate the carrying out of the LDV measurements and high speed shadowgrams and Schlieren in the side-on direction. Finally, the modelling effect on the pulsed combustor will continue.

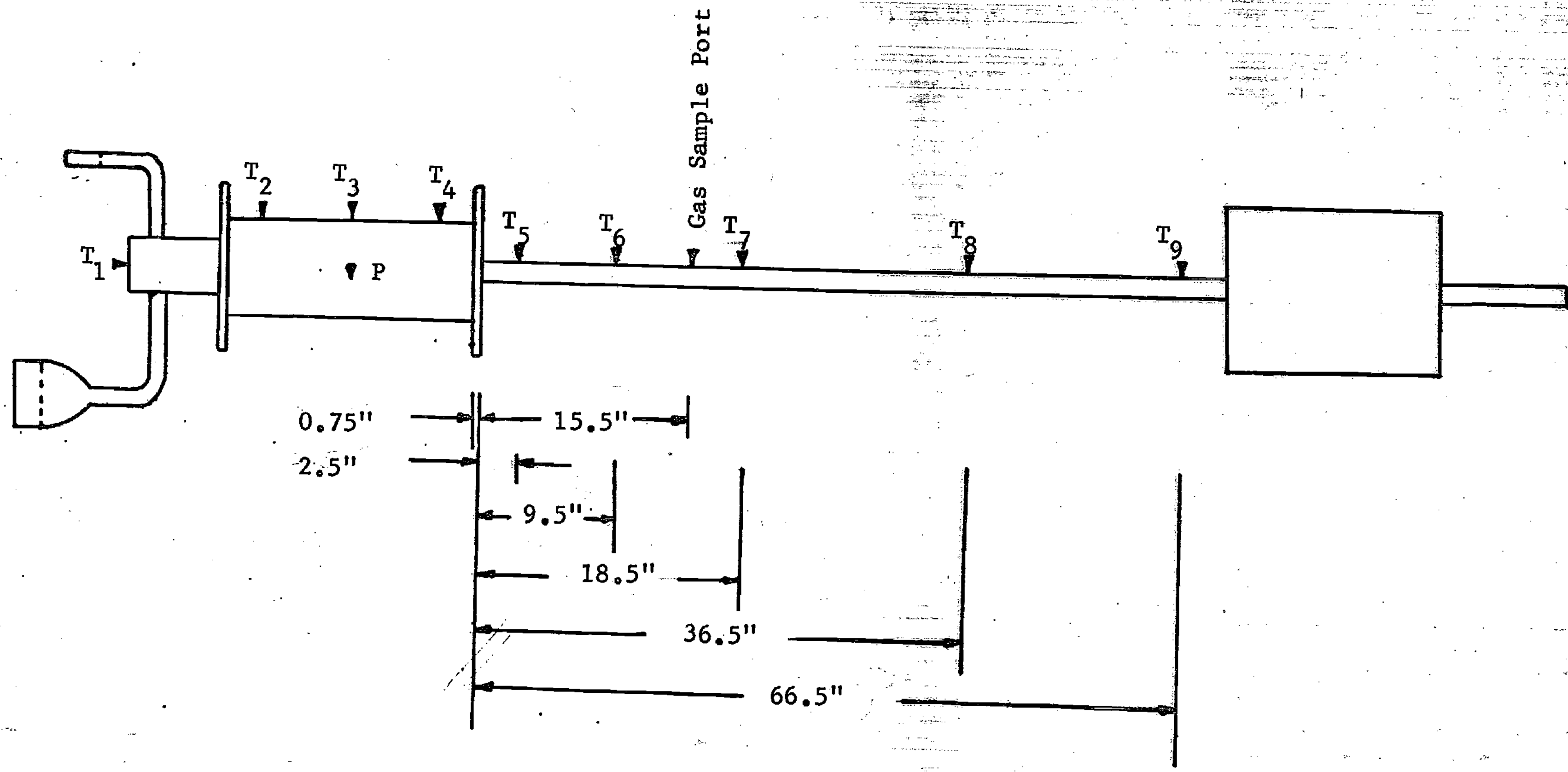


Figure 1. Location of Thermocouples.

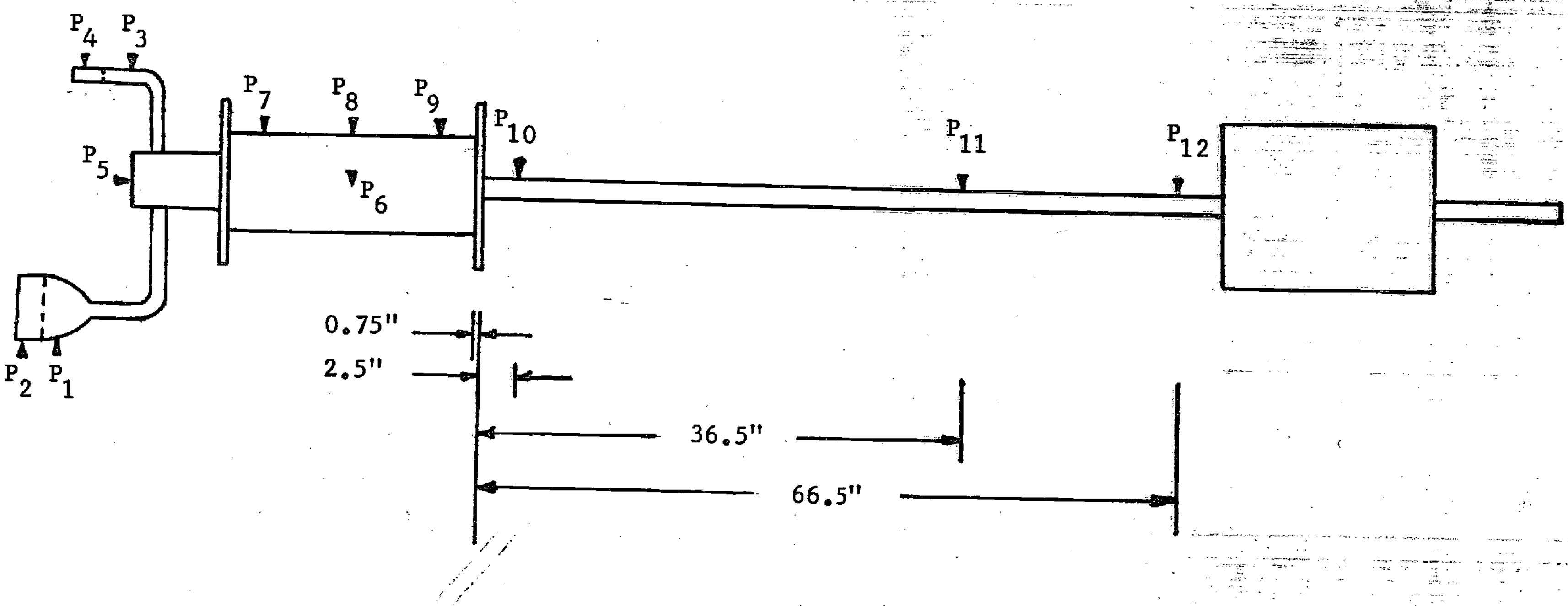


Figure 2. Location of Pressure Transducers.

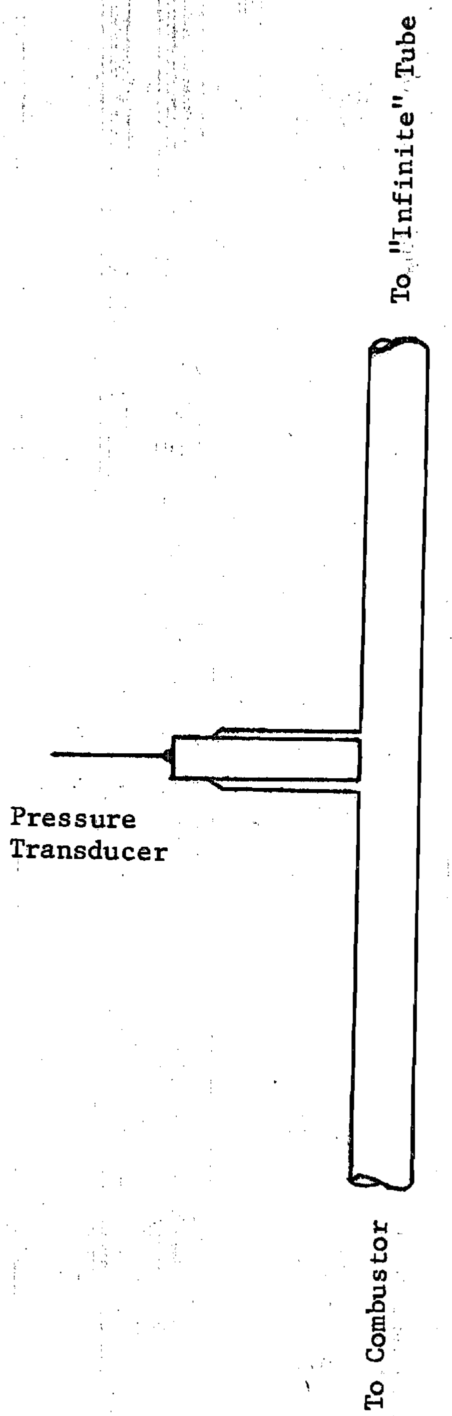


Figure 3. Pressure Transducer Arrangement.

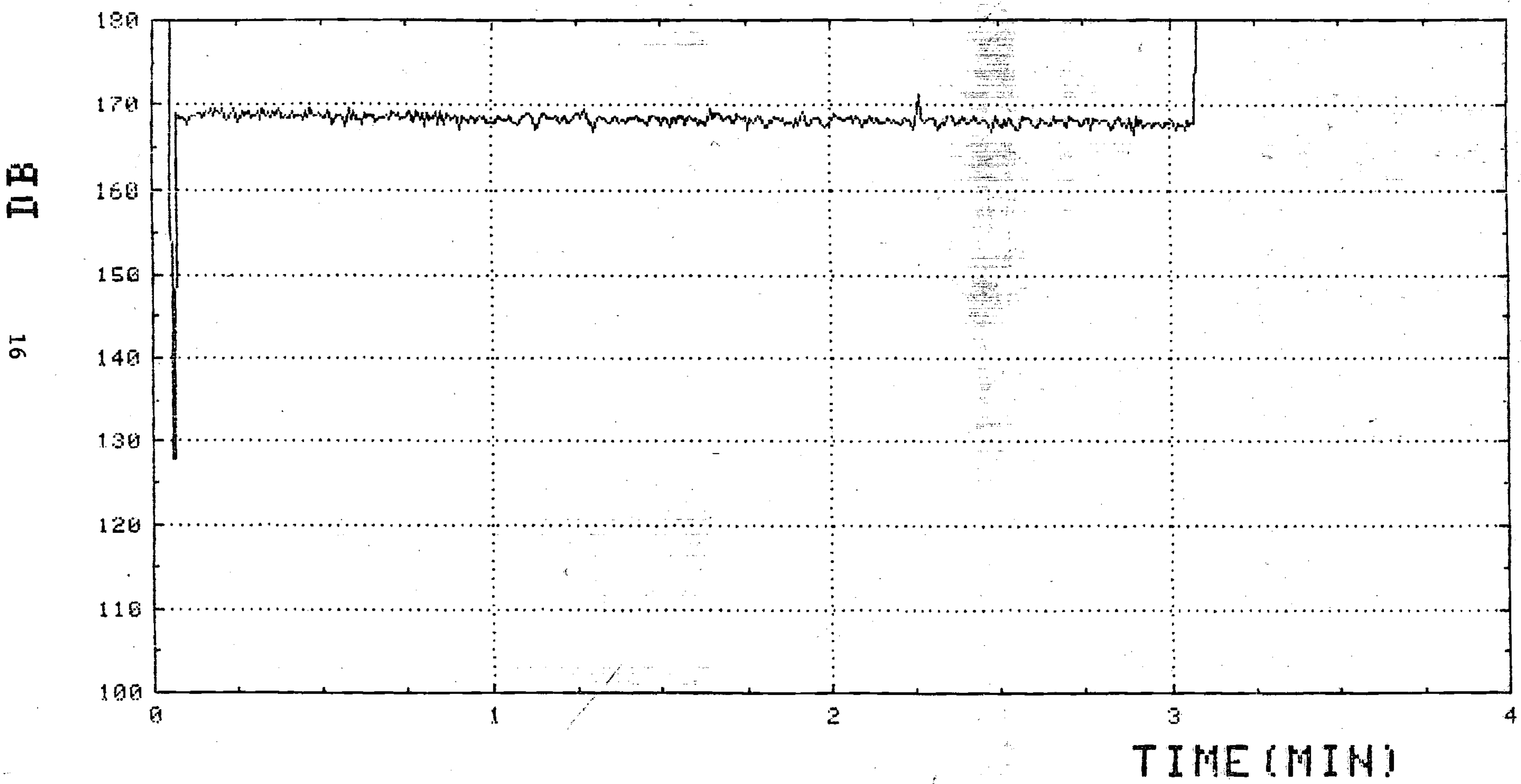
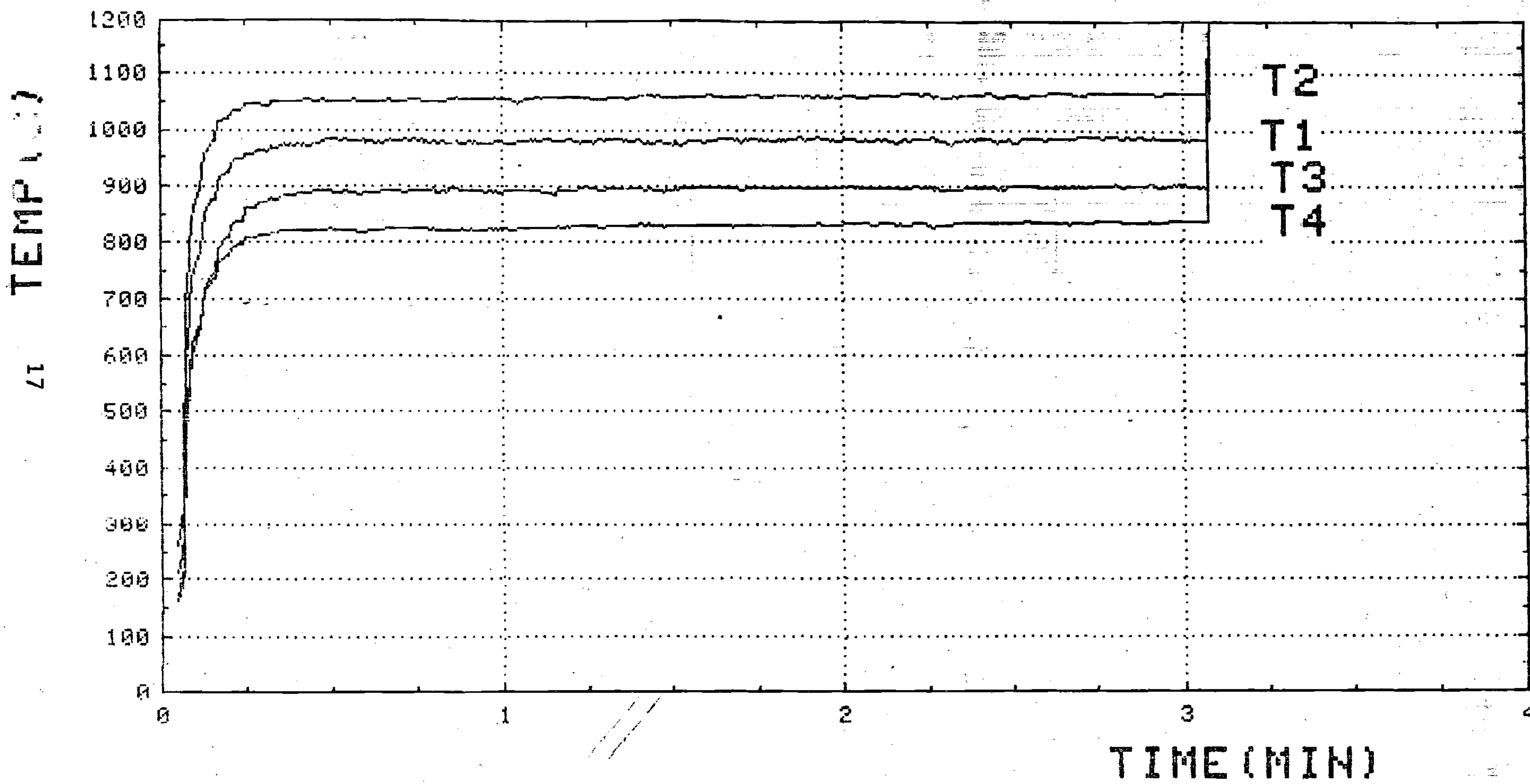


Figure 4. DB Level Variation with Time (Combustor 1, Eq. R = .62).



17

Figure 5. Temperature Variations with Time in Mixing and Combustion Chamber (Combustor 1, Eq. R = .62).

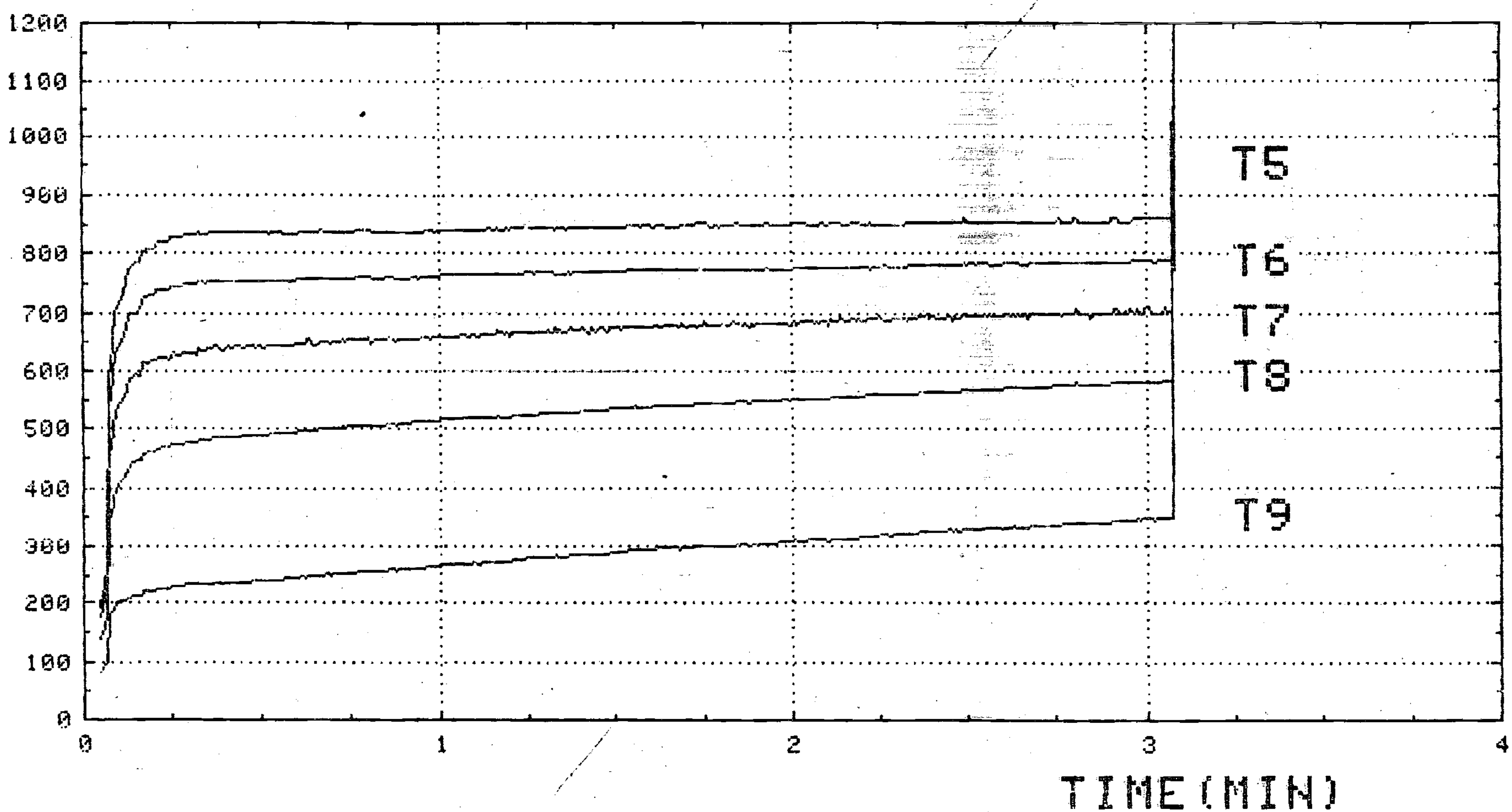


Figure 6. Temperature Variations with Time in Exhaust Pipe (Combustor 1, Eq. R. = .62).

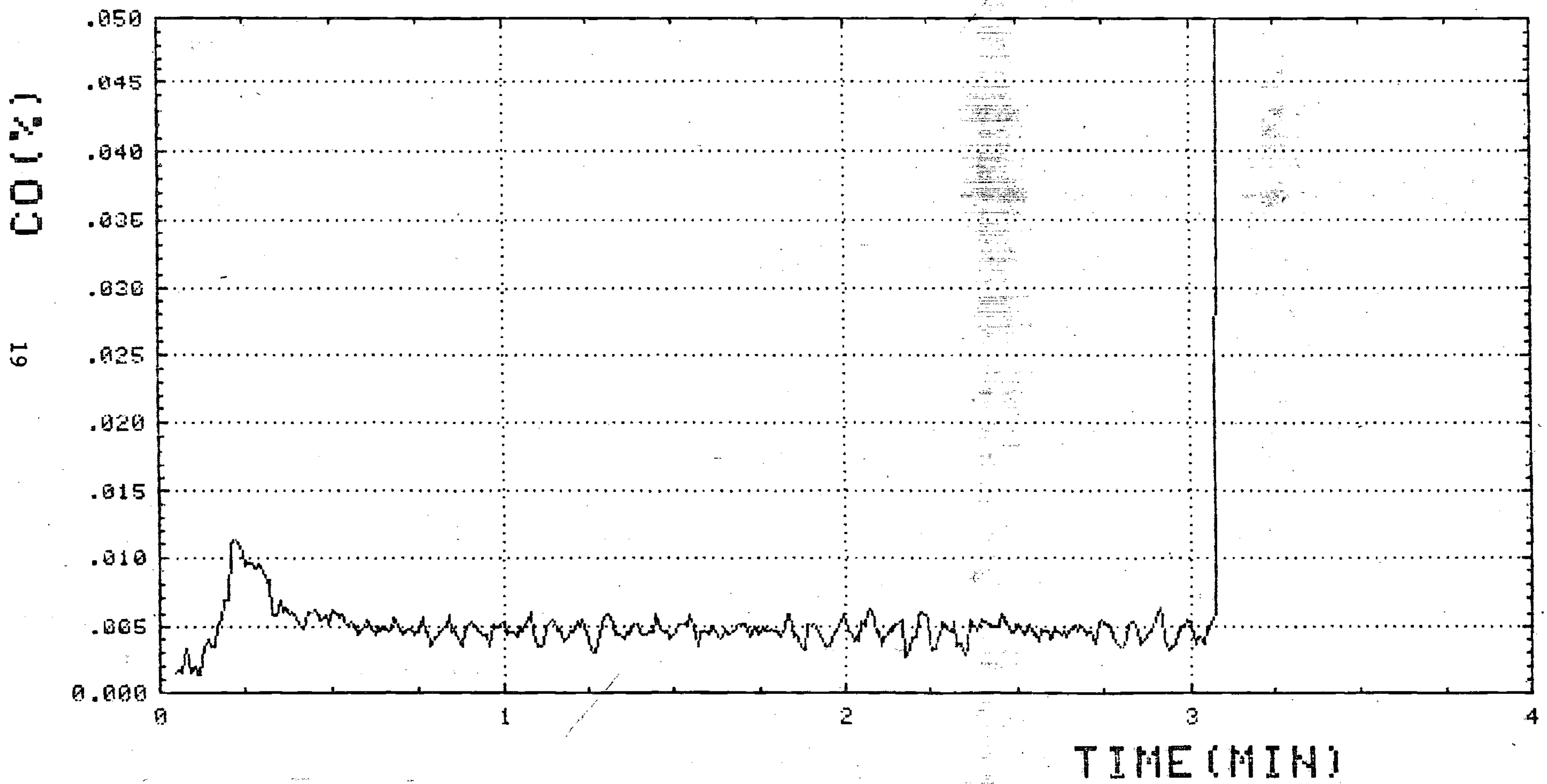


Figure 7. CO Concentration in Exhaust Gases vs. Time (Combustor 1, Eq. R. = .62).

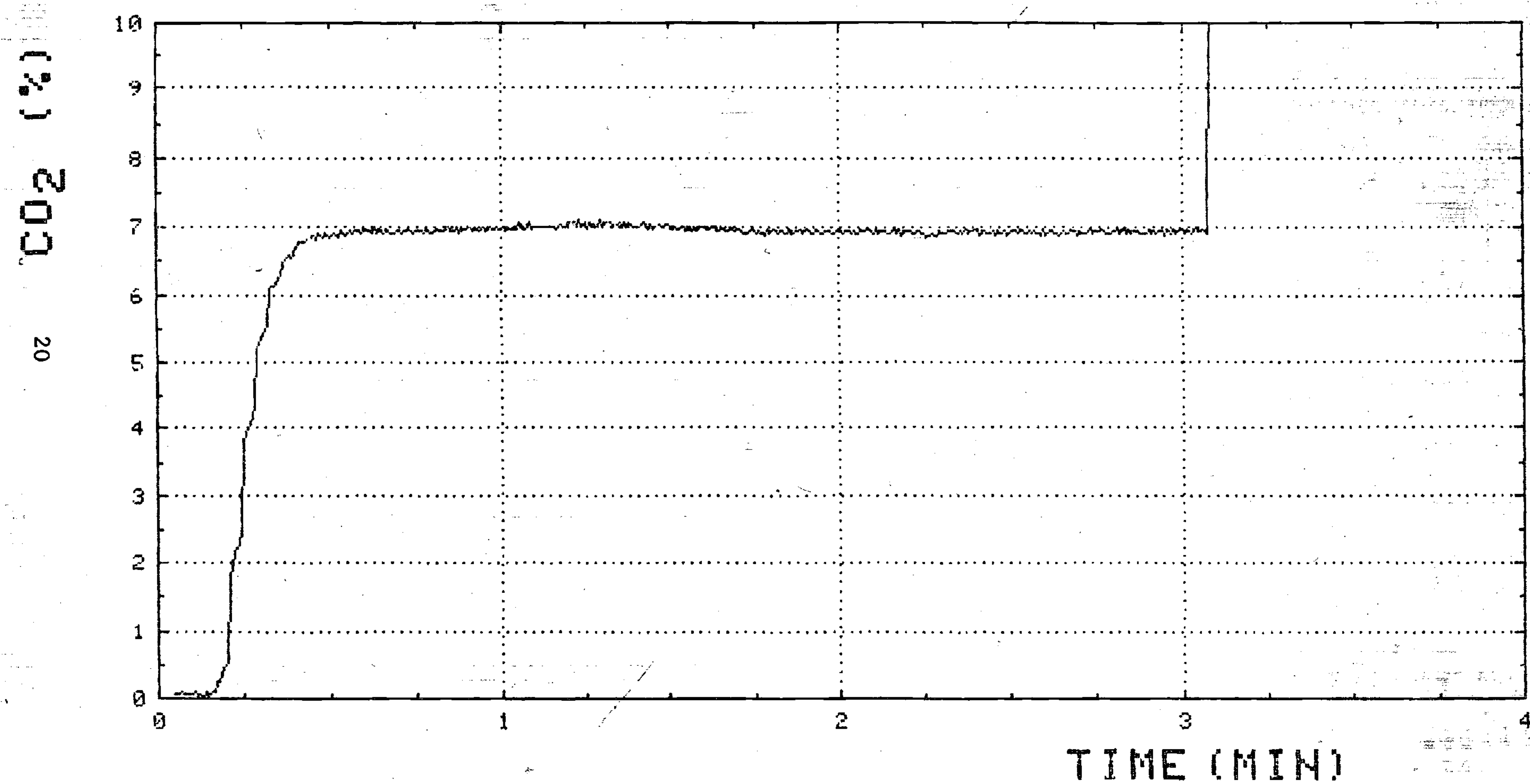


Figure 8. CO_2 Concentration in Exhaust Gases vs. Time (Combustor 1, Eq. R. = .62).

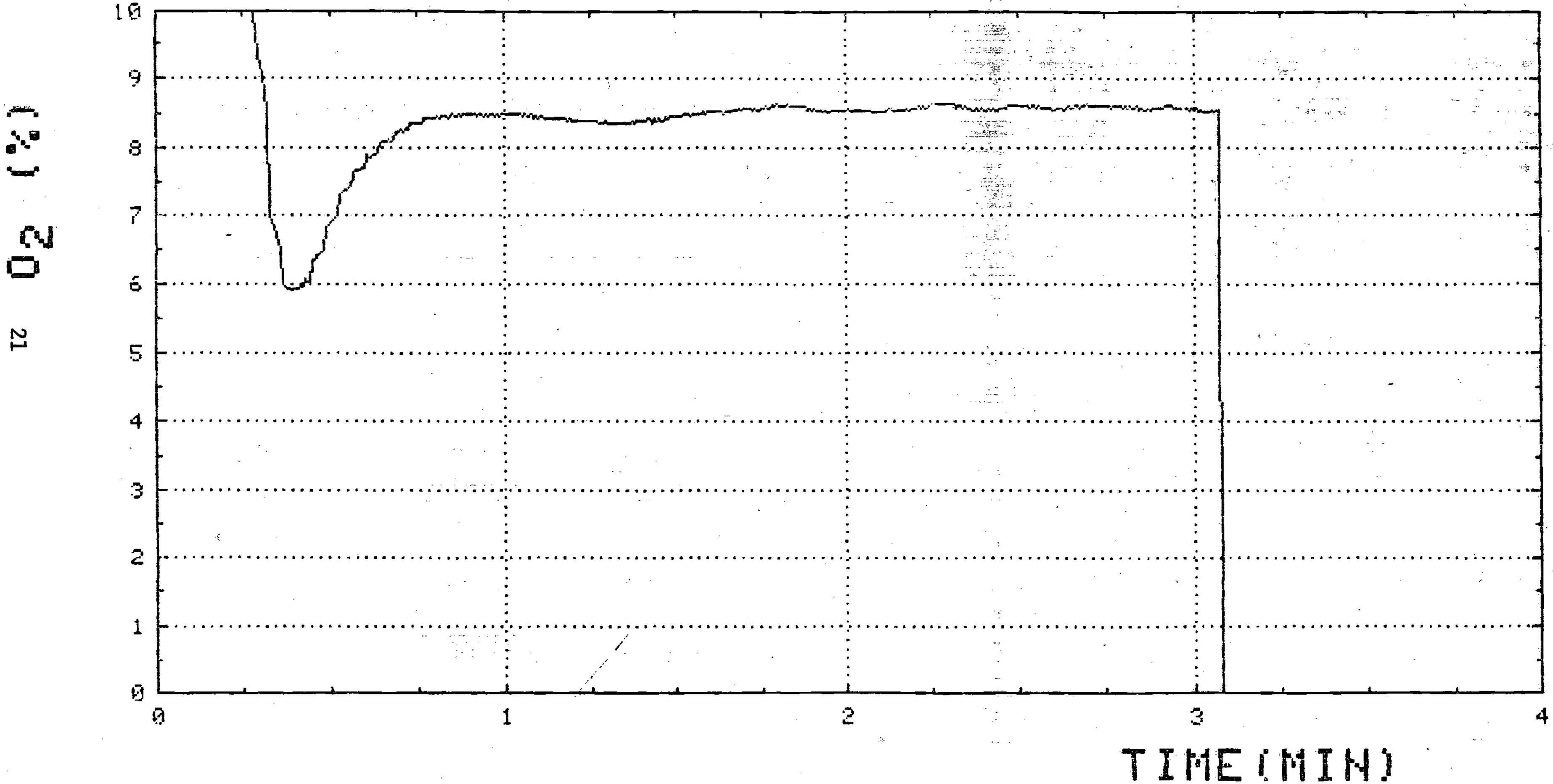


Figure 9. O_2 Concentration in Exhaust Gases vs. Time (Combustor 1, Eq. R. = .62).

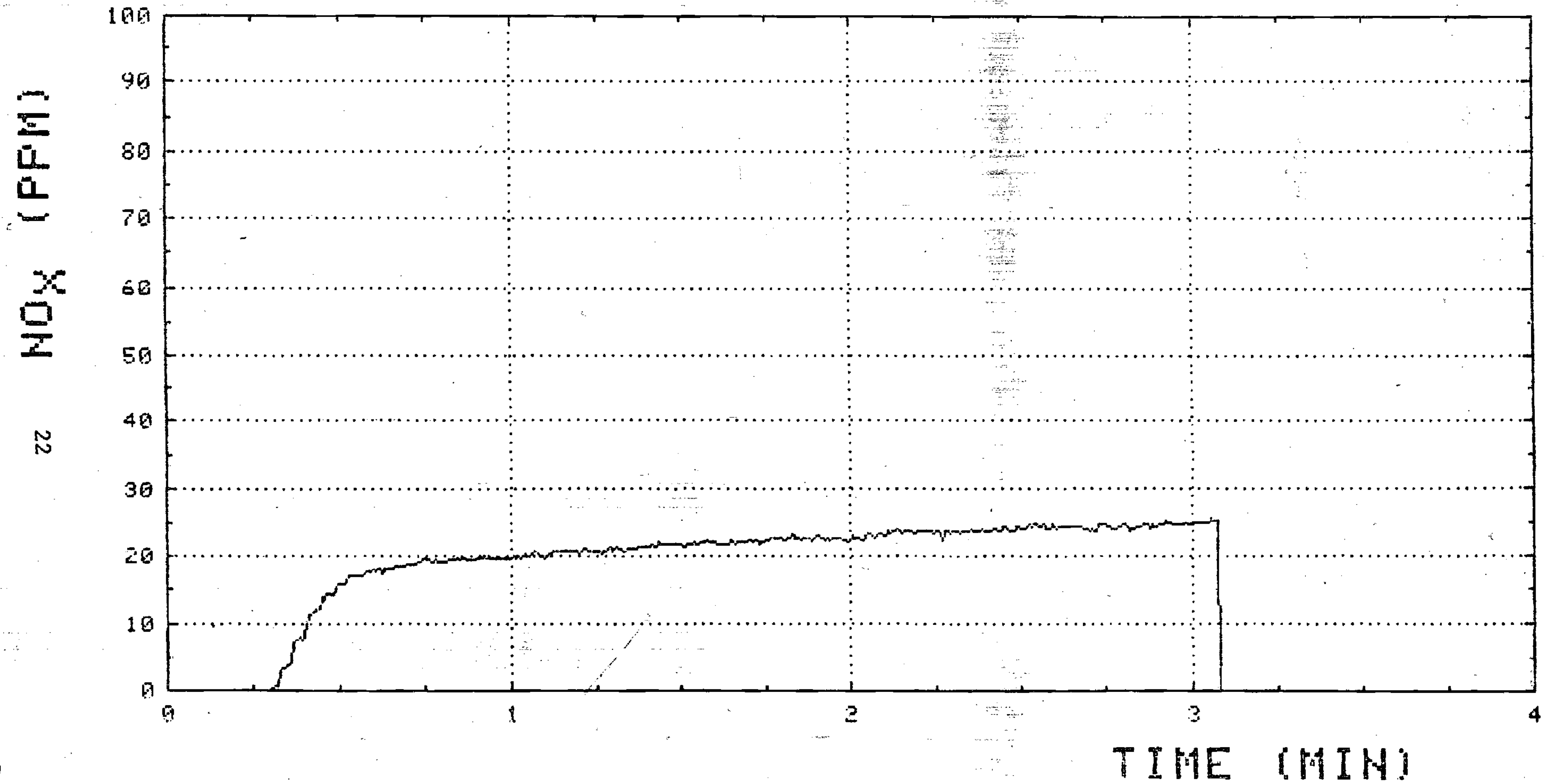


Figure 10. NO_x Concentration in Exhaust Gases vs. Time (Combustor 1, Eq. R. = .62).

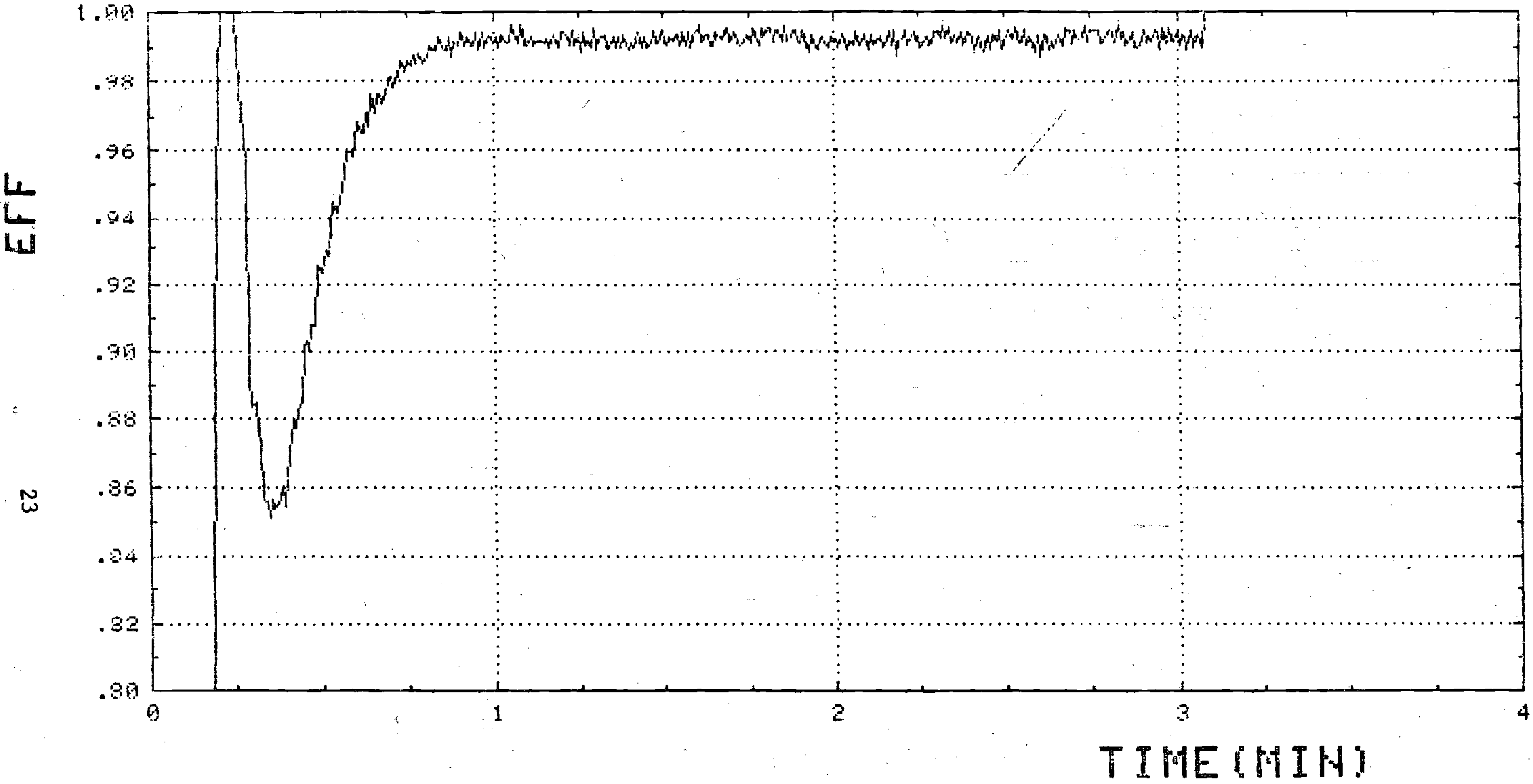


Figure 11. Combustion Efficiency vs. Time (Combustor 1, Eq. R. = .62).

Pulsating Burners - Controlling Mechanisms and Performance

Quarterly Report

June '85 - August '85

Prepared by

B. T. Zinn, B. R. Daniel and J. I. Jagoda

School of Aerospace Engineering

Georgia Institute of Technology

For

Gas Research Institute

Grant No. 5083-260-0873

GRI Project Manager

James A. Kezerle

Combustion

September 15, 1985

GRI DISCLAIMER

RESEARCH SUMMARY

Title	Pulsating Burners - Controlling Mechanisms and Performance
Contractor	Georgia Research Institute
Contract Number	GRI Grant 5083-260-0873
Principal Investigator	B. T. Zinn, B. R. Daniel and J. I. Jagoda
Objective	The objective of this study is to gain an understanding of the fundamental processes, such as mixing and cycle to cycle reignition, which control the operation of gas fired pulsed combustors. An analytical model is to be developed which will provide a rational procedure for the design and scaling of these burners.
Technical Perspective	In spite of the fact that gas fired pulsed combustors for home heating have now been on the market for a number of years, little is known about the physical and chemical processes which control the operation of these devices. Of particular interest are the mixing of fuel and air, cycle to cycle ignition and the nature of the flame propagation in the burner. Such information is necessary for improving the operational characteristics of existing pulsating combustors and for guidance in the development of new burners for increased capacity or novel applications. Furthermore, the acquired insight will be used to guide the development of a theoretical model for predicting the behavior of

pulsating combustors. The availability of such a model would permit the replacement of the costly empirical trial and error methods used to date for the design and scaling of pulsed combustors by a more rational approach.

<u>Technical Approach</u>

As a first step, a parametric study is being carried out using steel combustors in order to determine the influence of the combustor geometry on its performance and efficiency. Selected burners have and will be fabricated in pyrex and quartz and their flow field investigated using high speed cinematography Schlieren/shadowgraphy, stream line and mixing visualizations as well as laser Doppler velocimetry (LDV). Lastly, C-H and C-C spectroscopy is being used in the determination of the timing, location and rate of heat release during the combustion cycle. A linear and, if necessary, a non-linear theoretical model of the combustor is being developed to provide a basis for future pulsating combustor design and scaling.

<u>Program Plan</u>

The program is divided into three major tasks as outline below:

Task I - Experimental Investigation
- A Performance Evaluation
- B Flow Visualization:
  - a) streamline visualization
  - b) shadow/schlieren
- C Mixing Visualization
- D LDV
- E C-H & C-C Spectroscopy

Task II - Analytical Study

Task III - Reporting

Results

To date a test matrix for the parametric study of the performance of gas fired pulsating combustors (GFPC) has been developed. All components required to assemble 12 combustors of different geometries were fabricated. Pyrex end plates for the mixing and combustion chambers which can be used for all combustors have also been obtained and the hardware required to fit them to the combustors has been fabricated. A large decoupling chamber has been added upstream of the air valve which permits the measurement of the mean air flow rate. An all-pyrex combustor for optical diagnostics has been developed and tested. Early problems with explosions in the glass combustor during ignition have been solved. All these combustors are operational and have been extensively used. An exhaust gas analysis train to determine the combustion products composition and, thus, the combustion efficiencies has been designed and constructed. The individual detectors have been calibrated and testing has begun. A scheme for determining combustion efficiencies using both high and low heating valves from the analysis of the exhaust gases has been developed. The software for acquiring and analyzing the temperatures, pressures, exhaust gas compositions and combustion efficiencies of the combustor has been written for an HP series computer and successfully tested. A two component LDV system and the computer for its data acquisition have been set up and has been tested. An optical set-up for measuring C-C and C-H radiation and a high speed Schlieren and shadowgraphy system have been placed in operation. An expanded laser beam system for particle tracking and mixing visualizations has been set up and tested.

Initial performance tests have been carried out on all combustors in the test matrix. All combustors operated satisfactorily although the large volume combustors were somewhat more difficult to ignite. Analysis of the data, using a simplified model, showed that for the tested combustors the combustor volume is the parameter which controls the frequency of pulsations. This analysis also showed that the developed combustors operate as Helmholtz resonators. One combustor was designed and constructed for which the diameters of the mixing and combustion chambers were the same, thus effectively eliminating the step between mixing and combustion chamber. This combustor ran well and exhibited the same acoustic characteristics as a combustor with a step and equal volume, suggesting that the step does not influence the combustion process significantly.

Visual observation in the all-pyrex combustor showed that for this configuration most of the combustion actually takes place in the "mixing" chamber. High speed Schlieren and shadowgrams were used to visualize the incoming fuel and air jets, their mixing and combustion. Low sensitivity Schlieren was used to separate the Schlieren markings due to hot and cold gas interfaces from those due to flame fronts. C-H and C-C radiation from the combustor were measured for relatively lean, relatively rich and optimum combustion conditions. The latter correspond to those used in the visualization studies. These measurements strongly suggest that the combustion does not cease at any time during a cycle of operation. For a fixed fuel input, the magnitude of the radiation fluctuations decrease as the air inflow is reduced (i.e., the fuel/air ratio increases). Corresponding changes in the pressure fluctuations appeared considerably smaller. Comparison of the Schlieren and radiation results indicated that there is a pronounced increase in reaction rate when the fuel and air jets first mix.

A series of tests aimed at determining the performance of the developed combustors under various operating conditions has begun. First, the performance of the AGA combustor was investigated. During these tests temperatures and pressures were measured at various locations near the fuel and air flapper valves, in the mixing chamber, the combustion chamber and the exhaust pipe. Fuel and air flow rates were measured upstream of the flapper valves. At the same time, the concentration of CO, CO_2, O_2 and NO_x were measured in the exhaust gas. From these values the combustion efficiencies and the fuel equivalence ratios were calculated. The range of operation of the combustor was established by varying the air flapper valve settings. The combustor operated well at fuel equivalence ratios between 1.1 and .62. Very good performance was achieved for all conditions except near the rich limit. The frequency of oscillation ranged from 42 to 46 Hertz and the dB level from 167 to 169.5 for the various settings of the air flapper valve. The maximum temperature in the mixing chamber ranged from 935°C to 1035°C a short distance upstream of the combustor. This temperature increases to a higher value at the entrance of the combustor, after which it drops until it reaches about 450°C just before the decoupling chamber. The combustion efficiency was determined to be above 99.9% except near the rich limit where it dropped to 96% with CO levels of about 30 ppm and NO_x levels of 25 ppm at the lean limit rising to 55 ppm at stoichiometric and dropping slightly to 50 ppm at the rich limit.

Comparison of the above results with those obtained with the "stepless combustor" of equal volume showed that the performance is little affected by the step between the mixing and combustion chamber. In fact, equal air flapper valve settings resulted in the same air and fuel flow rates in both combustors. The limits of operation of both combustors are very similar as are the concentrations of combustion products in the exhaust gases. The efficiencies are equal at 99.8% although they fall off more steeply in the stepless combustor near the rich limit. The dB level, however, is about 1.5 dB higher in the stepless combustor while all the temperatures are about 30-50°C lower than in the AGA combustor.

Flow visualizations using particle tracking were carried out using still photography and the optical set-up described above. The particle tracks are clearly visible showing the air entering the mixing chamber and the ensuing turbulent mixing. However, in order to obtain a better understanding of the flow patterns within the combustor high speed motion pictures of the particle tracks will be required.

INTRODUCTION

The objective of this study is to gain insight into the fundamental processes responsible for the operation of gas fired combustors and to develop an analytical model capable of predicting the performance characteristics of new pulsed combustor designs. Furthermore, the model will consider the effect of scaling upon combustor performance. To this end, the effects of a number of geometrical combustor parameters such as L/D ratios, combustor volume and exhaust pipe length and diameter upon the combustor performance are under investigation. Measurements include the determination of temperature and pressure distributions, combustion efficiencies, NO_x levels in the exhaust gases and fuel air ratios for the different combustion under various operating conditions. Also, the interactions between the pulsed flow field and combustion processes are being studied. Special emphasis is placed on determining the source and location of the cyclic ignition and following the flame spread in the combustor. The streamlines in the flow field and the mixing of fuel and air are being visualized and recorded. Velocities are measured using LDV. An analytical model is being developed which will predict the performance of combustors having different geometries and scales. The insights gained from the above experiments will be used in the development of the model which will, in turn, be tested against further experimental data. It is, thus, anticipated that this study will enable the industry to abandon the hereto used empirical approach in the design and development of pulsed combustors in favor of a rational design procedure based upon dependable model predictions.

PROGRAM PLAN

The program is divided into three major tasks as outlined below:

Task I-Experimental Investigation

A. Performance Evaluation. The performance of a number of combustors of different geometries (i.e., different L/D, volumes, tail pipe lengths, etc.) is being investigated using temperature, pressure and combustion efficiency measurements. For each configuration, the performance is evaluated over a range of air/fuel ratios and fuel loadings.

B. Flow Visualization. Stream lines are being investigated by recording the tracks of seed particles moving through a laser light sheet. This process is repeated with the laser sheet at different combustor locations. Refractive index gradients caused by the flame front or by pockets of hot and cold gases are visualized using Schlieren and shadowgraphy.

C. Mixing Visualization. Mixing patterns are being recorded photographically by heavily seeding either the fuel or the air and illuminating the transparent combustor using a laser light sheet. Again, the visualization is repeated with the laser sheet at different combustor locations.

D. LDV. Although the bulk of the laser Doppler velocimetry measurements will be carried out in the second and third years, the system has been set up during the first year. The data acquisition system previously developed is being modified to permit ensemble averaging over a number of cycles. An additional combustor with flat walls is being fabricated in order to avoid the problem of beam displacement due to the cylindrical walls.

E. C-H & C-C Spectroscopy. Although this part of the study was originally reserved for the second and third years, some measurements were already carried out and significant results obtained. Radiation from the combustor is passed through the respective filters and its intensity measured using a photomultiplier. The radiation measurements are then related to combustion intensities.

Task II - Analytical Study

A theoretical model which describes the performance of the investigated combustors is being developed. The model incorporates the findings of the experimental phases of the program. The model is linear and investigates the possible range of operating conditions of the burners. Should this not result in satisfactory agreement with the experimental data, the non-linearities of the problem will be incorporated in the model.

Task III - Reporting

As per contract agreement.

TECHNICAL PROGRESS AND RESULTS

During the past reporting period (June '85 - August '85) detailed performance and efficiency tests were continued. For these studies, each combustor is tested in two different instrumentation configurations using pressure transducers, thermocouples and the exhaust gas sampling train as described in the last progress report. Detailed results obtained with the No. I AGA combustor and the No. II combustor will be presented in this report. Combustor No. II has the same volume as combustor No. I, but in No. II the diameter of the mixing and combustion chamber are equal, thus eliminating the step between the two chambers. Both combustors were tested over the full range of fuel/air ratios over which they are operational by varying the air flapper valve settings.

Both combustors exhibited similar characteristics. Combustor No. I is capable of sustaining pulsating operation for fuel/air ratios between .63 and 1.03 while combustor No. II is operational for Φ between .62 and 1.08. Thus, for both combustors successful operation is possible for fuel/air ratios slightly above stoichiometric, contrary to findings of earlier studies. As mentioned in previous reports, the fuel/air ratios are being determined in 2 different way; that is, one by direct measurement of the air and fuel flow rates and the other using the chemical analysis of the exhaust gases. Values of Φ obtained by these two means agree to within approximately 1-2%. At the same time the additional decoupling chamber in the air line required for air flow rate measurements was shown to have little effect on the combustor performance.

Figure 1 shows the fuel and air flow rates for both combustors as a function of air flapper valve setting. Clearly, the difference in geometry between combustors No. I and No. II does not affect the reactant flow rates. Not surprisingly, the mean air flow rate for both combustors increases as the air flapper is opened further. At the same time, however, fuel flow rate decreases by about 15% over the range of combustor operation.

The combustion efficiencies of both combustors are very high (> 99.8%) independent of whether one uses high or low heating valves in the calculation. A decrease in efficiencies is only observed near the rich limits with the efficiencies of combustor No. II dropping much more sharply than those for combustor No. I, see Fig. 2. At this point it should be noted that the actual value of the efficiencies near the rich limit in Fig. 2 may be slightly in error, since the unburnt hydrocarbons in the exhaust have so far not been measured. This is not a problem for conditions of high combustion efficiencies since the level of only 30 ppm of CO in the exhaust gases strongly suggests that no unburnt hydrocarbons are present under those conditions. A gas chromatograph has been converted to act as an unburnt hydrocarbon analyzer and will now be used to detect the presence of unburnt hydrocarbon, if any, in the exhaust gases at the rich limit. At the same time the dB level in both combustors rise slightly as the fuel air ratio increases towards stoichiometric. The level in combustor No. I is generally about 1-2 dB lower than that in combustor No. II, see Fig. 3.

The level of CO in the exhaust gases was found to be extremely low over the entire range of combustor operation except near the rich limit where it rises sharply for both combustors. The small differences between the two combustors noticeable in Fig. 4 is not significant since the CO detector is not accurate at levels below 50 ppm. Other exhaust gas concentrations such as CO_2 and O_2 are essentially identical for the two combustors, CO_2 increasing and O_2 decreasing with increasing stoichiometry.

The final constituent measured in the exhaust gases, NO_x, was also found to be very similar for combustors I and II see Fig. 5. As expected, the NO_x generated increases with the fuel/air ratio up to about stoichiometric after which it falls off. This fall off is more pronounced in combustor No. I.

The change of the temperature in the axial direction is similar to that reported in the last progress report for all fuel/air ratios for both combustors; that is, the highest temperature was measured at a position just downstream of the mixing chamber in the combustion chamber. At all locations the maximum temperatures were recorded close to stoichiometric with temperatures being slightly lower below and above stoichiometric. Temperatures in the stepless combustor are some 30-50^{o}C higher than in combustor No. I everywhere except at the location of maximum temperature where the temperatures are the same in both combustors for all fuel/air ratios. This equality in temperature is probably related to the identical levels of NO_x concentrations found in both combustors. Examples of the temperature variations with Φ at different locations in the two combustors are shown in Fig. 6. The temperature subscripts are the same as those used in the last progress report. In summary, the above reported results strongly suggest that the combustion process is not significantly influenced by the differences in geometry between combustors No. I and No. II. Damping and heat transfer, however, do seem to be affected by the changes in geometry as shown by the measured differences in dB levels and temperatures.

In addition to the performance tests described above the flow visualization using particle tracking was continued. Good particle tracks were obtained using still photography on 400 ASA film at 1/500 sec exposure time. The particles used to seed the air flow are about 40 microns in diameter and thus do not follow precisely the rapidly fluctuating, turbulent motion of the gases but they do follow the general overall flow pattern. In fact the still photograph clearly show the air jet entering the mixing chamber as well as the random turbulent motion later in the cycle. However, in order to better understand the complex flow pattern in the mixing chamber a high speed motion recording of the particle tracks will be required. The development of an analytical model continued during the reporting period.

PLANNED WORK

During the next reporting period the performance tests for combustors of different volumes, lengths and diameters under a variety of fuel/air ratios will be continued. Streamline visualizations will be carried out using high speed motion pictures. Also high speed Schlieren will be continued with special emphasis on conditions of marginal combustor performance such as that near the rich limit. The new combustor with flat side glass windows for LDV measurements should be completed during the next three months. Finally, the modelling effort on the pulse combustor will continue.

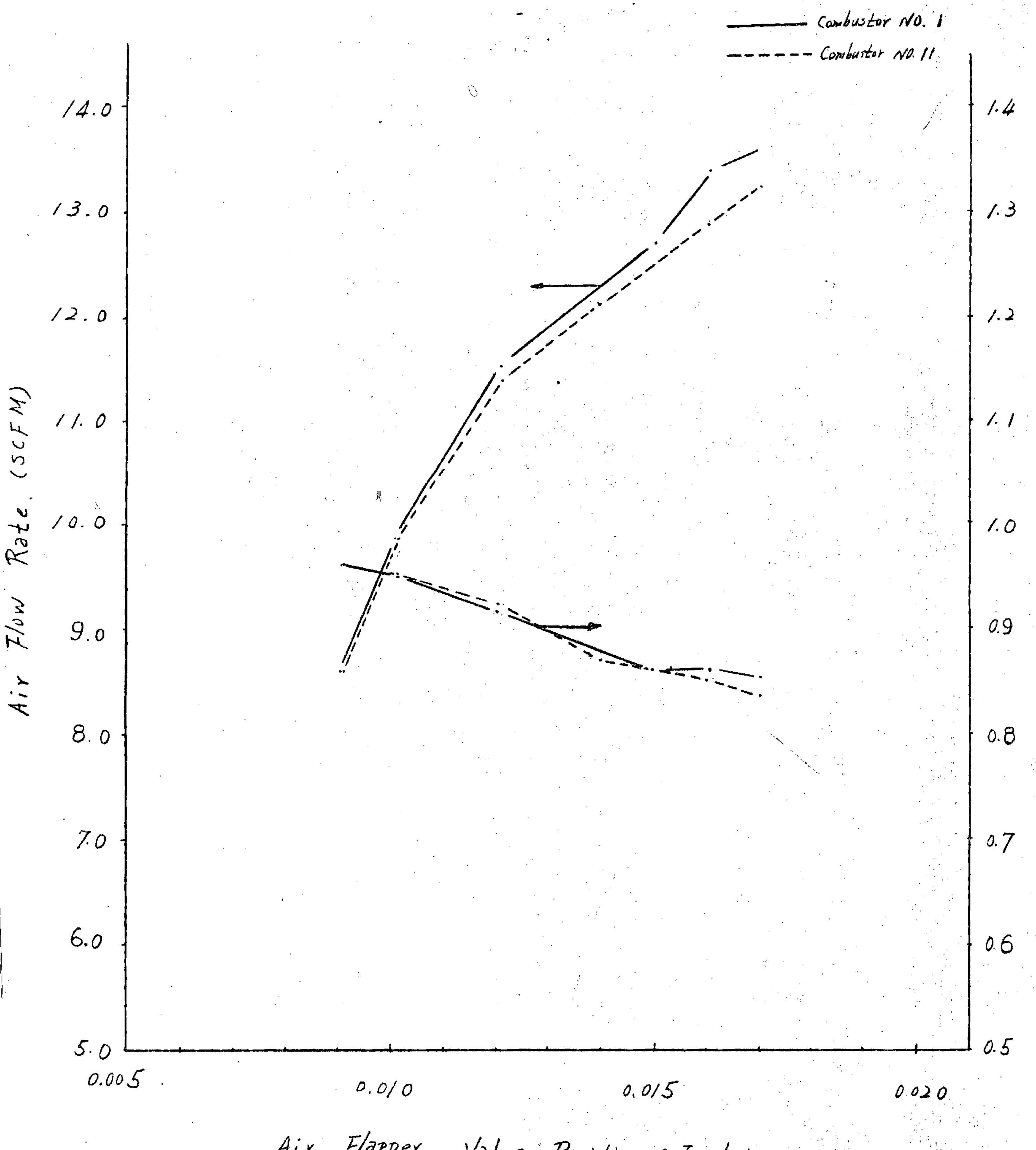


Fig. 1. Air and Fuel Flow Rates vs. Air Flapper Valve Settings for Combustors No. I and No. II.

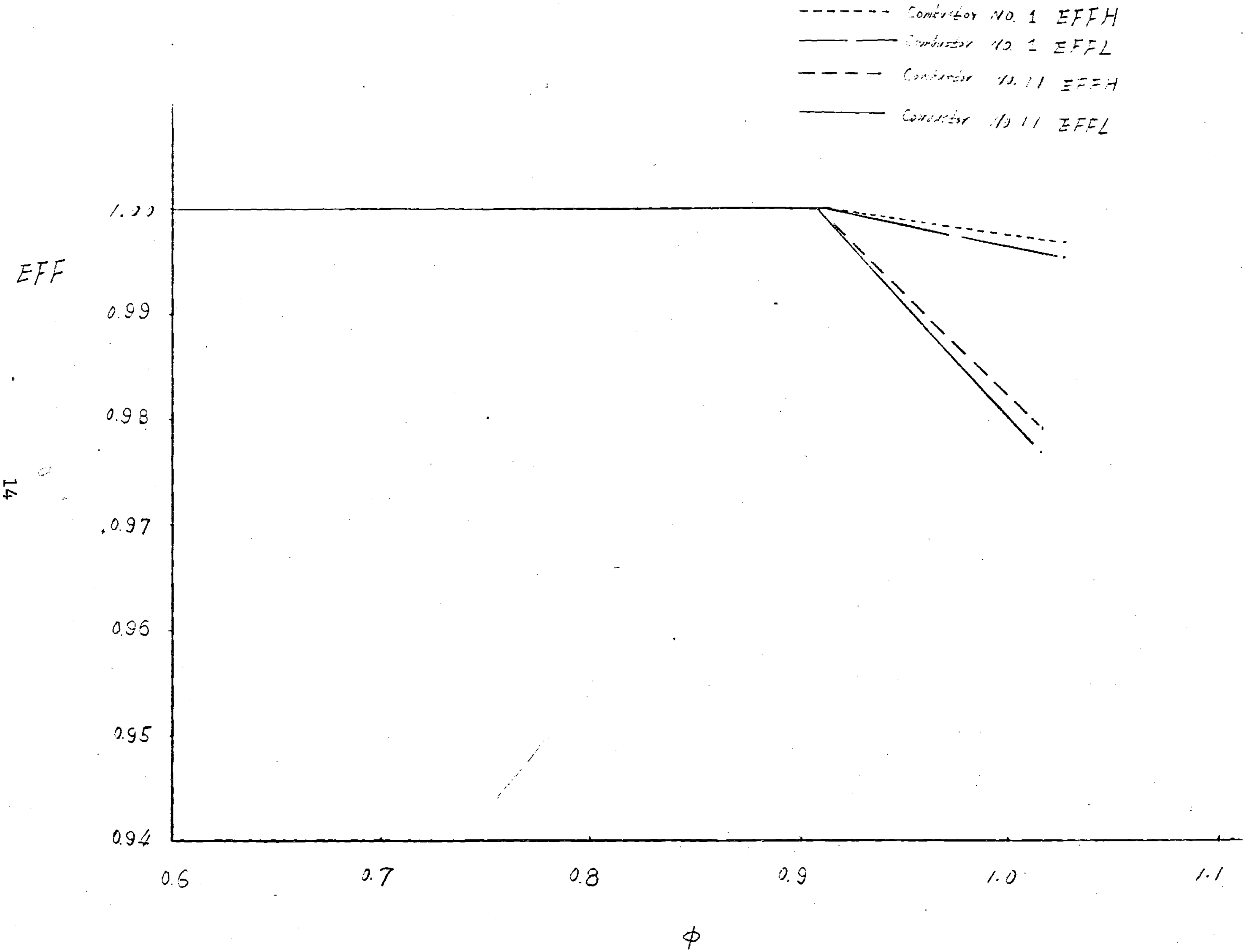


Fig. 2. Efficiencies Based on High and Low Heating Values vs. Fuel/Air Ratios for Combustors No. I and No. II.

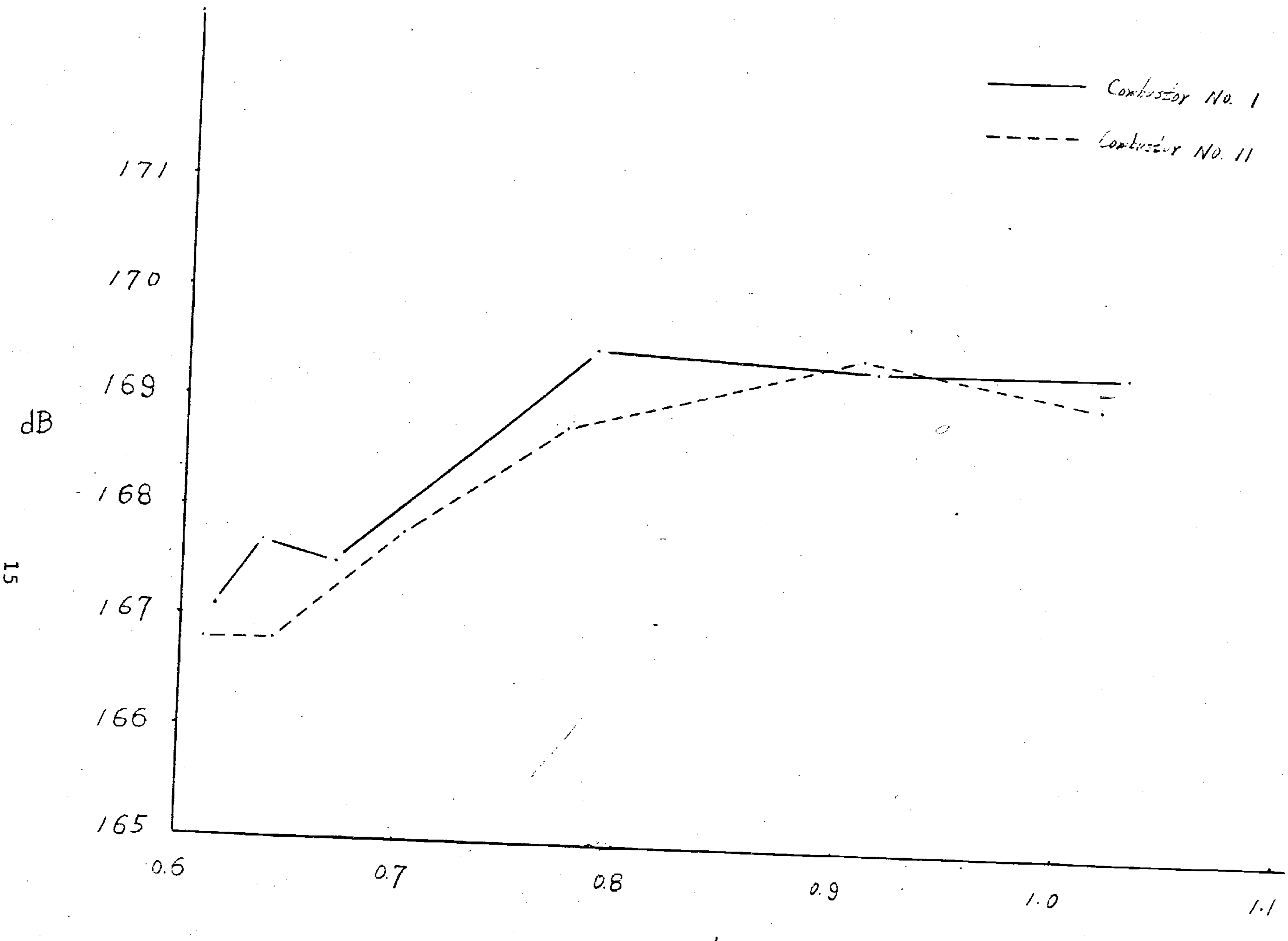


Fig. 3. DB Levels vs. Fuel/Air Ratios for Combustors No. I and No. II.

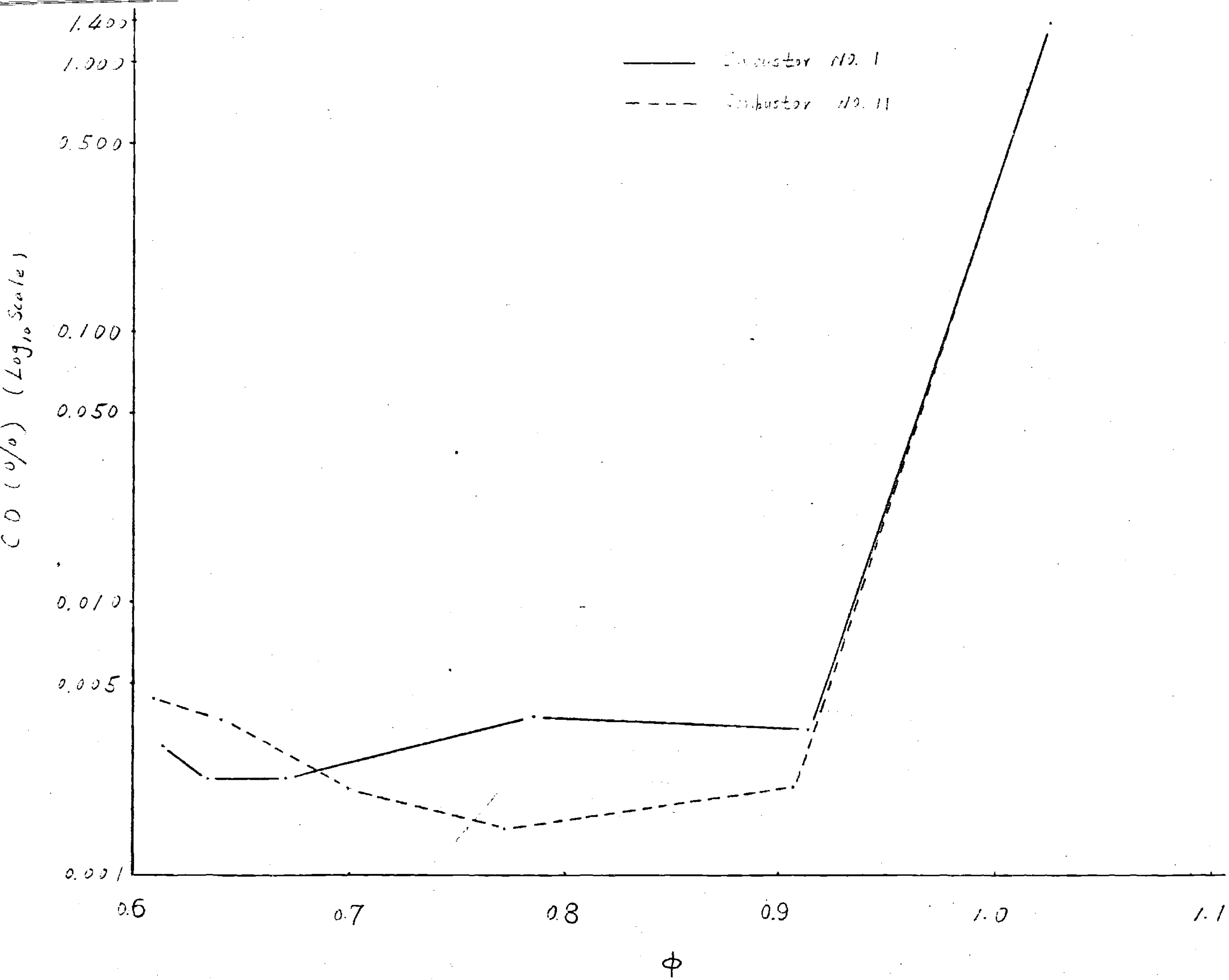


Fig. 4. CO Level in the Exhaust vs. Fuel/Air Ratio for Combustors No. I and No. II.

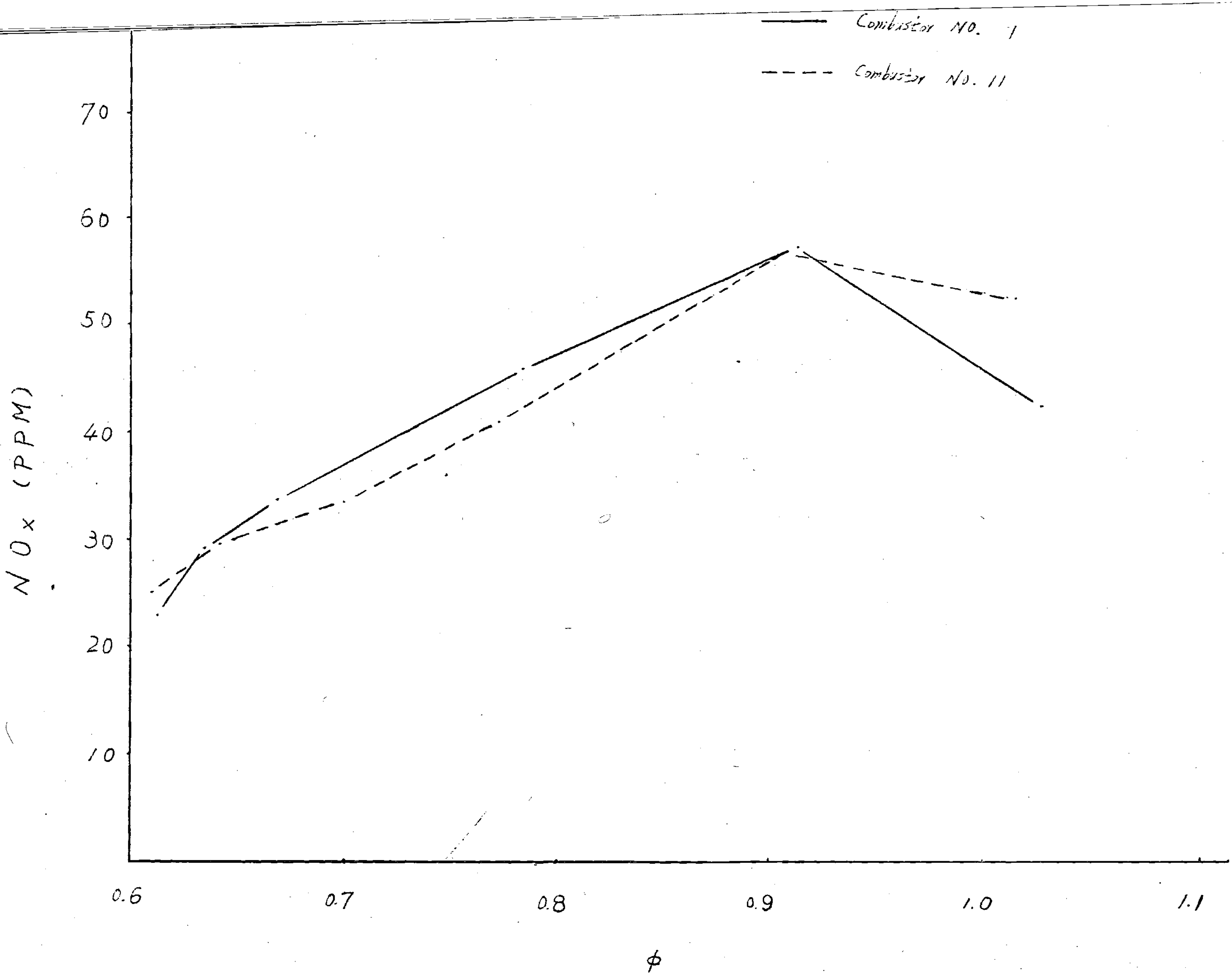


Fig. 5. NO_x Level in the Exhaust vs. Fuel/Air for Combustors No. I and No. II.

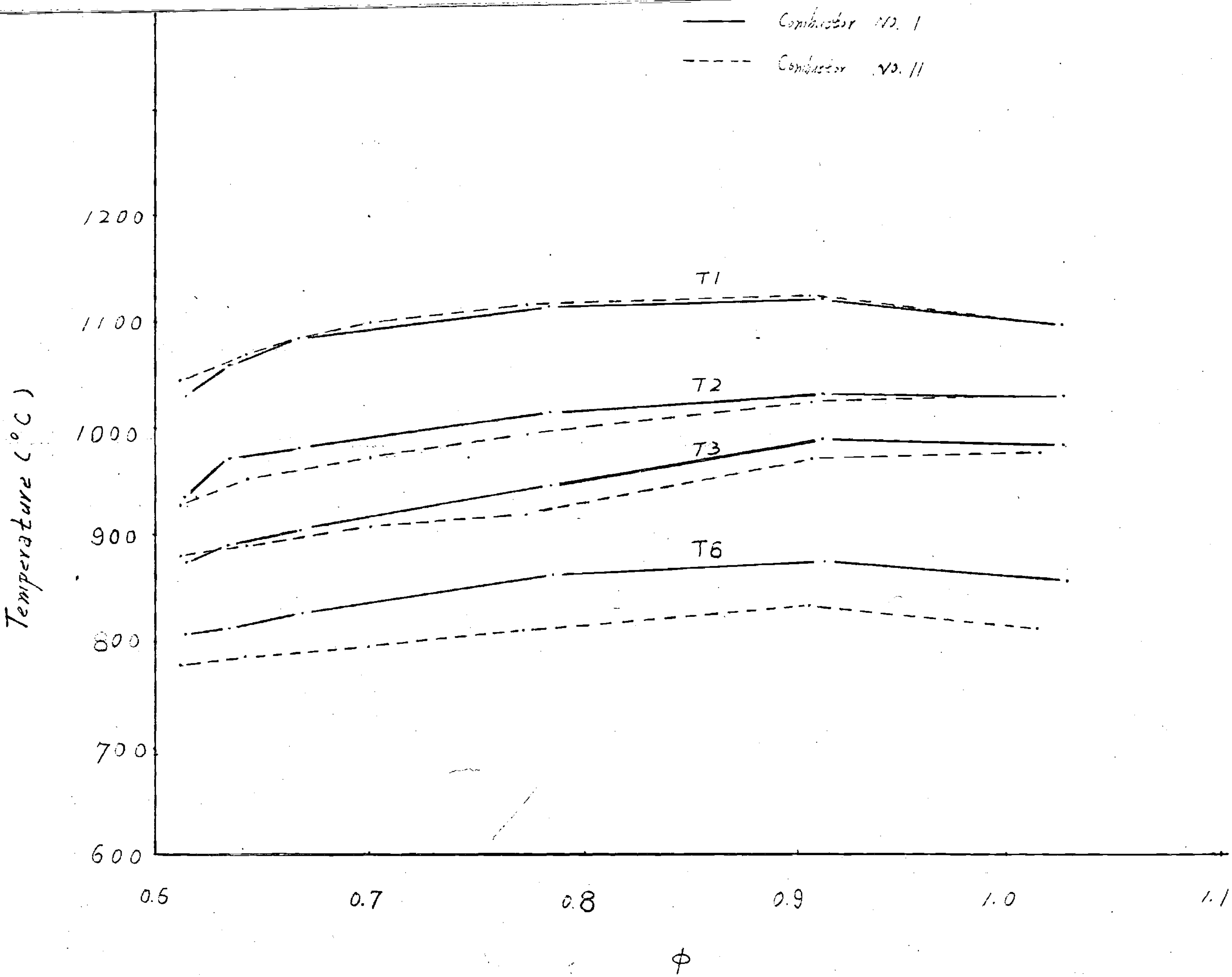


Fig. 6. Temperatures in the Mixing Chamber, the Combustion Chamber and the Tail Pipe vs. Fuel/Air Ratio for Combustors No. I and No. II.

E-16-662

Pulsating Burners - Controlling Mechanisms and Performance

Quarterly Report

December 1985 - February 1986

Prepared by

B. T. Zinn, B. R. Daniel and J. I. Jagoda

School of Aerospace Engineering

Georgia Institute of Technology

For

Gas Research Institute

Grant No. 5083-260-0873

GRI/85-0032

GRI Project Manager

James A. Kezerle

Combustion

March 15, 1986

GRI DISCLAIMER

RESEARCH SUMMARY

Title	Pulsating Burners - Controlling Mechanisms and Performance
Contractor	Georgia Tech Research Institute
Contract Number	GRI Grant 5083-260-0873
Report Period	December 1985 - February 1986 Quarterly Report
Principal Investigator	B. T. Zinn, B. R. Daniel and J. I. Jagoda
Objective	The objective of this study is to gain an understanding of the fundamental processes, such as mixing and cycle to cycle reignition, which control the operation of gas fired pulse combustors. An analytical model is to be developed which will provide a rational procedure for the design and scaling of these burners.
Technical Perspective	In spite of the fact that gas fired pulse combustors for home heating have now been on the market for a number of years, little is known about the physical and chemical processes which control the operation of these devices. Of particular interest are the mixing of fuel and air, cycle to cycle ignition and the nature of the flame propagation in the burner. Such information is necessary for improving the operational characteristics of existing pulsating combustors and for guidance in the development of new burners for increased capacity or novel applications. Furthermore, the acquired insight will

be used to guide the development of a theoretical model for predicting the behavior of pulsating combustors. The availability of such a model would permit the replacement of the costly empirical trial and error methods used to date for the design and scaling of pulsed combustors by a more rational approach.

Technical Approach

As a first step, a parametric study is being carried out using steel combustors in order to determine the influence of the combustor geometry and fuel air ratio on its performance and efficiency. Selected burners have been and are being fabricated in pyrex and quartz and their flow field investigated using high speed cinematography Schlieren/shadowgraphy, stream line and mixing visualizations as well as laser Doppler velocimetry (LDV). Lastly, C-H and C-C spectroscopy is being used in the determination of the timing, location and rate of heat release during the combustion cycle. A linear and, if necessary, a non-linear theoretical model of the combustor is being developed to provide a basis for future pulsating combustor design and scaling.

Program Plan:

The program is divided into three distinct tasks outlined below:

Task I - Experimental Investigation
- A Performance
- B Flow Visualization
  - a) streamline visualization
  - b) shadow/Schlieren
- C Mixing Visualization

C LDV

E C-H & C-C Spectroscopy

Task II - Analytical Study

Task III - Reporting

Results

During this reporting period new high speed shadowgraphy records were obtained for the combustor operating near its limts of operation, as well as at the optimum fuel/air ratio. These films show more clearly than previous movies the structure of the fuel and air jets entering the mixing chamber and their interaction with each other. Significant differences were noted in the timing of the fuel and air injection. The mixing patterns just prior to reactant injection for the cases near the lean and rich operating limits were also different from that at optimum fuel-air ratio.

The gas chromatograph which had previously been converted for use as an unburnt hydrocarbon analyzer was calibrated. Unburnt hydrocarbons in the exhaust of one combustor were measured for different fuel-air ratios. For fuel-air ratios away from the limits of operation of the combustor, where the combustor efficiencies approach unity, very low unburnt hydrocarbon concentrations ($\sim$ 1 ppm) were measured. Near the limits of operation the unburnt hydrocarbon levels increase to approximately 50 ppm near the lean limit and 1000 ppm or more near the rich limit. The relatively high levels of unburnt hydrocarbons near the lean operational limit are indicative of the deficiencies in the mixing process under these conditions.

The measurement of acoustic pressures in different parts of the combustors operating with different fuel/air ratios was continued during this reporting period. A data reduction routine has been adapted to analyze the pressure traces in order to obtain frequencies and amplitudes of the pressure signals and to determine the phase angle between acoustic pressures in different combustor locations. Primary frequencies and higher harmonics were measured and a phase shift of 180° was observed between pressures measured in the combustion chamber and those in the exhaust pipe. Finally, the starting procedure for the pulse combustor was modified to permit the monitoring of the growth and decay of the acoustic pressures during start up and shut down. It is anticipated that these measurements will result in a determination of the driving and damping characteristics of the different combustors.

INTRODUCTION

The objective of this study is to gain insight into the fundamental processes responsible for the operation of gas fired pulsed combustors and to develop an analytical model capable of predicting the performance characteristics of new pulsed combustor designs. Furthermore, the model will consider the effect of scaling upon combustor performance. To this end, the effects of a number of geometrical combustor parameters, such as L/D ratio, combustor volume and exhaust pipe length and diameter, upon the combustor performance are under investigation. Also, the interactions between the pulsed flow field and combustion processes are being studied. Special emphasis is placed on determining the source and location of the cyclic ignition and following the flame spread in the combustor. The streamlines in the flow field and the mixing of fuel and air are being visualized and recorded. Velocities are measured using LDV. An analytical model is being developed which will predict the performance of combustors having different geometries and scales. The insights gained from the above experiments will be used in the development of the model which will, in turn, be tested against further experimental data. It is, thus, anticipated that this study will enable the industry to abandon the currently used empirical approach in the design and development of pulsed combustors in favor of a rational design procedure based upon dependable model predictions.

Program Plan

The program is divided into three major tasks as outlined below:

Task I - Experimental Investigation

A. Performance Evaluation. The performance of a number of combustors of different geometries (i.e., different L/D, volumes, tail pipe lengths, etc.) is being investigated using temperature, pressure and combustion efficiency measurements. For each configuration, the performance is evaluated over a range of air/fuel ratios and fuel loadings.

B. Flow Visualization. Stream lines are being investigated by recording the tracks of seed particles moving through a laser light sheet. This process is repeated with the laser sheet at different combustor locations. Refractive index gradients caused by the flame front or by pockets of hot and cold gases are visualized using Schlieren and shadowgraphy.

C. Mixing Visualization. Mixing patterns are being recorded photographically by heavily seeding either the fuel or the air and illuminating the transparent combustor using a laser light sheet. Again, the visualization is repeated with the laser sheet at different combustor locations.

D. LDV. A 2-D Laser Doppler Velocimeter has been set up and tested, and is used to measure velocities at selected stations in the mixing and combustion chamber and in the tail pipe. The data acquisition system previously developed is being modified to permit ensemble averaging over a number of cycles. A special combustor is being fabricated in order to avoid the problem of beam displacement due to the cylindrical walls.

E. C-H & C-C Spectroscopy. In this part of the study radiation from the combustor is passed through the respective filters and its intensity measured using a photomultiplier. The radiation measurements are then related to combustion intensities. These are then compared with the phase measurements of mixing as determined from the high speed shadowgrams and with the instant of ignition as recorded using high speed, low sensitivity Schlieren.

Task II - Analytical Study

A theoretical model which describes the performance of the investigated combustors is being developed. The model will incorporate the findings of the experimental phases of the program. The model will be linear and investigate the possible range of operating conditions of the burners.

Task III - Reporting

As per contract agreement.

TECHNICAL PROGRESS AND RESULTS

During the past reporting period (Dec. '85 - Feb. '86) high speed shadowgram movies were obtained for the first time, for the pulse combustor operating near its lean and rich limits. New shadowgrams were also recorded at the optimum fuel/air ratio of the combustor. Through improved orientation of the optics, these movies indicate more clearly the detailed structure of the fuel and air jets showing particularly well the large vortices attached to the leading edge of the air jet. The general features of the flow under optimum conditions were very similar to the ones observed in previous high speed shadowgraphs for the same condition. However, significant differences were observed between the flow fields under optimum conditions and those observed near the limits of operation of the combustor. In particular, the timing of the injection of the fuel and air jets and their mixing changed significantly with changing fuel/air ratio. As shown in Table I the arrival of the air jet in the mixing chamber was delayed as the gap in the air flapper valve was reduced. This resulted in the reactants mixing later in the cycle and, for the rich limit condition, an increase of approximately 15% in the duration of each cycle.

The gas chromatograph which had previously been converted for use as an unburnt hydrocarbon analyzer was calibrated using a standard certified 100 ppm methane in nitrogen mixture. Unburnt hydrocarbon concentrations in the exhaust of one of the combustors were measured for different fuel air ratios. For air flapper valve settings away from the limits of operation of the combustor unburnt hydrocarbon levels of only 1 ppm were measured. Near the rich limit of operation these levels increased to approximately 1000 pm. If the combustor is operated at a fuel/air ratio of 1.05 (where it will only pulsate as long as the spark ignition source is left on), 3000 ppm of unburnt hydrocarbon were measured in the exhaust. Near the lean limit of operation up to 320 ppm of unburnt hydrocarbon were detected during the first three minutes after turning on the combustor. Once the combustor has heated up, after about 5 minutes, the hydrocarbon level drops to values of the order of 30-50 ppm. A similar drop was also observed for the CO level during the heating up stage of the combustor. These relatively elevated levels of unburnt fuel near the lean limit of operation of the combustor are indicative of imperfect mixing under these conditions.

Acoustic pressures were measured in different parts of some of the combustors for different fuel air ratios. Four pressure signals, one each from the mixing chamber, the combustion chamber, the beginning and the end of the tail pipe were simultaneously digitized and stored on the computer disc. A data reduction routine was developed which permits the display of the time traces of acoustic pressure. A fast Fourier transform is then performed on the data and auto correlations and cross correlations are determined on each channel and between any two channels. This permits the determination of the acoustic pressure spectra and of the phase angle between any two fluctuating pressure traces.

Figure 1 shows pressure-time traces for one combustor at the four locations. The pressure traces in the mixing and combustion chamber and at the head of the exhaust pipe are clearly sinosoidal at constant frequency, although there are some fluctuations in amplitude. The dB levels of these three acoustic pressures lie within less than 2 dB of each other. Near the end of the exhaust pipe just upstream of the decoupling chamber the signal becomes much more erratic with higher harmonics contributing significantly. This is accompanied by a drop of about 20 dB. The mixes of frequencies present are shown in the spectra in Figure 2. For the signals obtained in the mixing chamber, the combustion chamber and at the head of the exhaust pipe almost all the acoustic energy lies in the main frequency with only small contributions from the 1st harmonic. Near the decoupling chamber, however, harmonic frequencies up to the eighth harmonic carry significant amounts of energy. In addition frequencies away from the simple harmonics appear to make a significant contribution. This effect is, most likely, caused by the reflection of the acoustic waves at the exhaust pipe-decoupler interface. Furthermore, the pressure oscillations in the mixing and combustion chamber are exactly in phase with each other but 180° out of phase with those in the exhaust pipe.

Finally, the growth and decay rates of the fluctuating pressure signals are being measured for the purpose of being able to use these rates to determine the driving and damping characteristics of the combustor. With this in mind the starting procedure for the pulse combustor has been modified to permit starting with a single spark and with the addition of only minimal amounts of auxiliary air introduced through the air flapper valve. Early tests have shown that constant pressure amplitudes are generally reached within three cycles. In order to extend those start-up periods for a better determination of the growth rates and thus the combustors driving characteristics, test will be carried out in which the damping of the system will be increased.

PLANNED WORK

During the next reporting period measurements will be continued to determine the concentration of unburnt hydrocarbons near the limit of operation of all the combustors for which full performance tests have been carried out. In addition, the acoustic pressure fluctuations will be monitored for these combustors for various fuel/air ratios. These measurements will be performed during steady operation as well as during start up and shut down. From the experimental growth and decay observations it will be attempted to determine the driving and damping characteristics of the combustors.

The new combustor with flat side windows for LDV measurements will be completed. The LDV system will be readied for the measurements and its data acquisition program updated for ensemble averaging of the measured velocities. Finally, the modeling effect on the pulse combustor will continue.

Table I. Timing (in msec) of various events in the cycle for the combustor operating with different fuel/air ratios.

	Fuel jet enter	Air jet enters	Air jet impinges on fuel jet	Complete cycle
Lean limit	0	1.55	3.35	25.18
Optimum setting	0	3.5	6.0	23.75
Rich limit	0	6.9	9.2	28.80

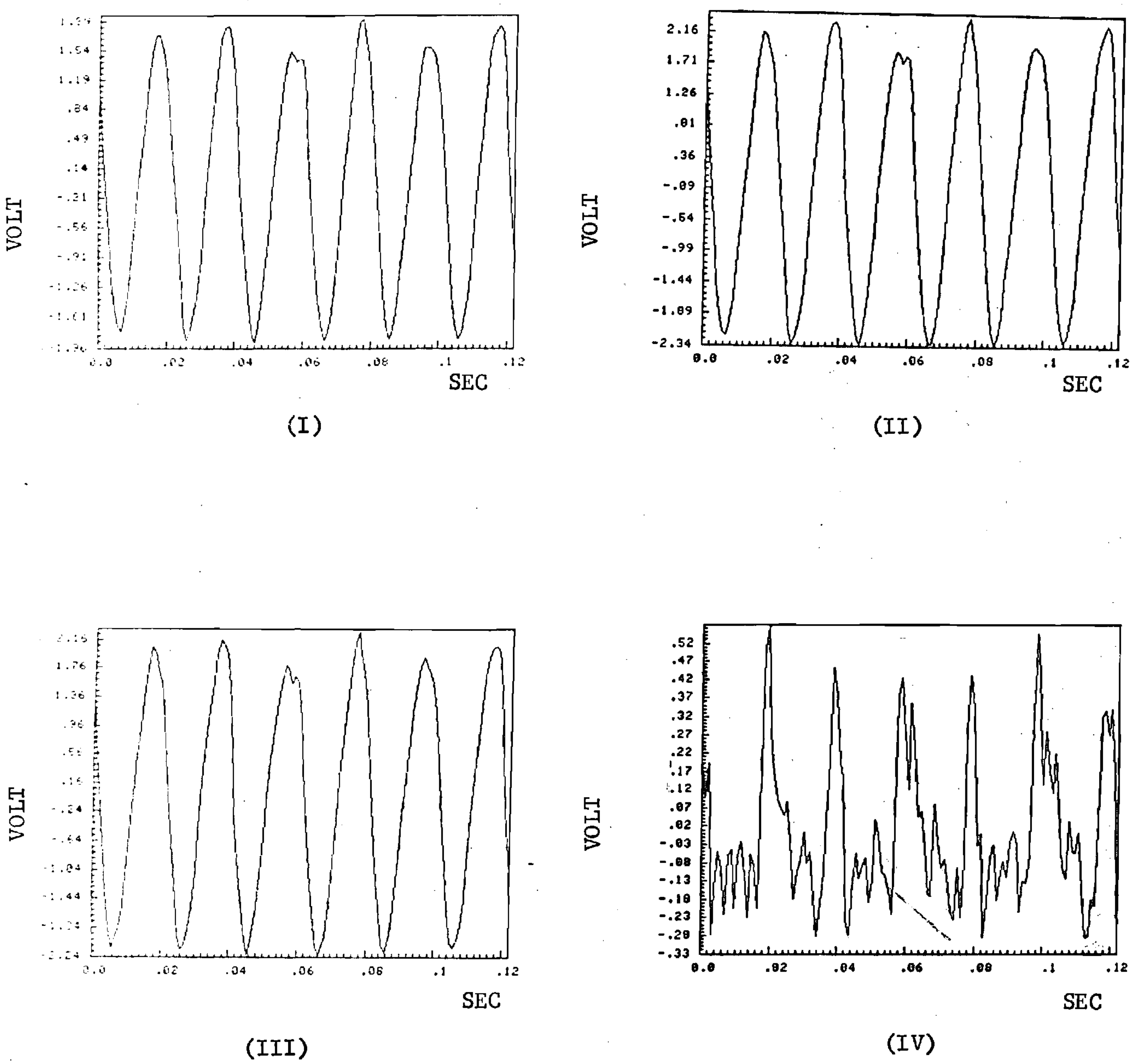


Figure 1a. Acoustic Pressure Traces for Optimum Fuel/Air Ratio (I) in Mixing Chamber, (II) in Combustion Chamber, (III) at the Head of Exhaust Pipe, (IV) at the Exit of Exhaust Pipe.

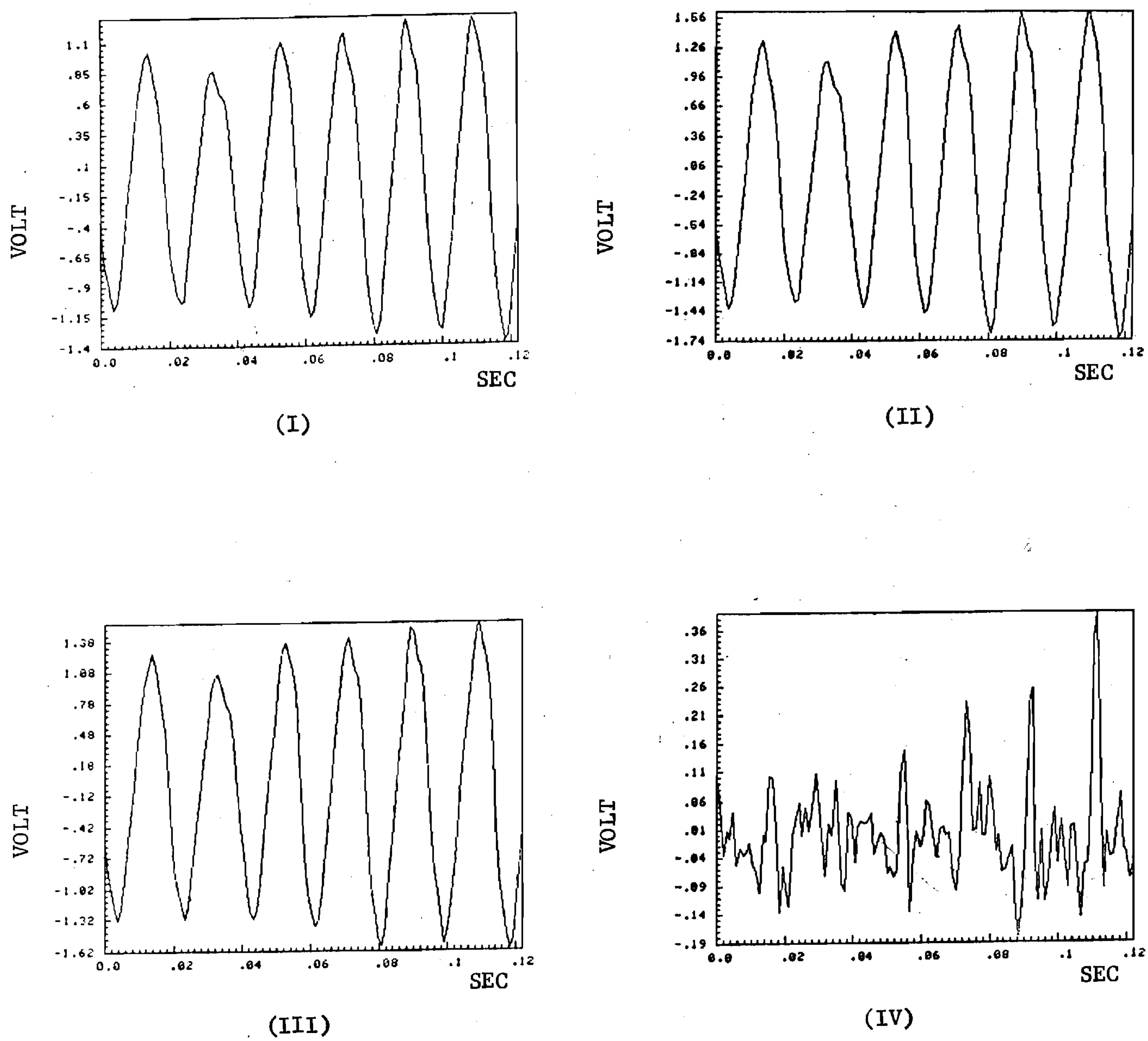


Figure 1b. Acoustic Pressure Traces near Lean Limit of Operation (I) in Mixing Chamber, (II) in Combustion Chamber, (III) at the Head of Exhaust Pipe, (IV) at the Exit of Exhaust Pipe.

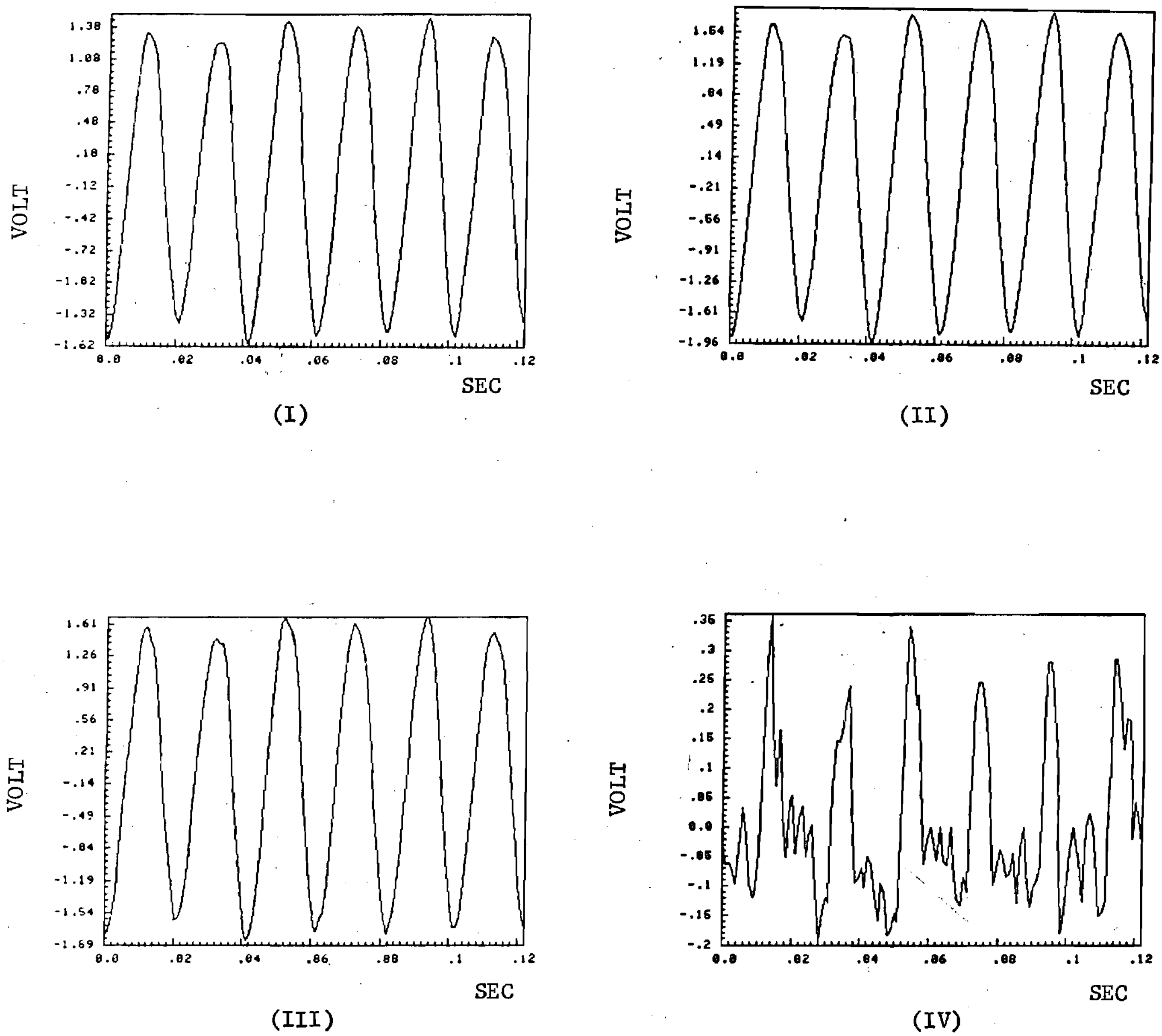


Figure 1c. Acoustic Pressure Traces near Rich Limit of Operation. (I) in Mixing Chamber, (II) in Combustion Chamber, (III) at the Head of Exhaust Pipe, (IV) at the Exit of Exhaust Pipe.

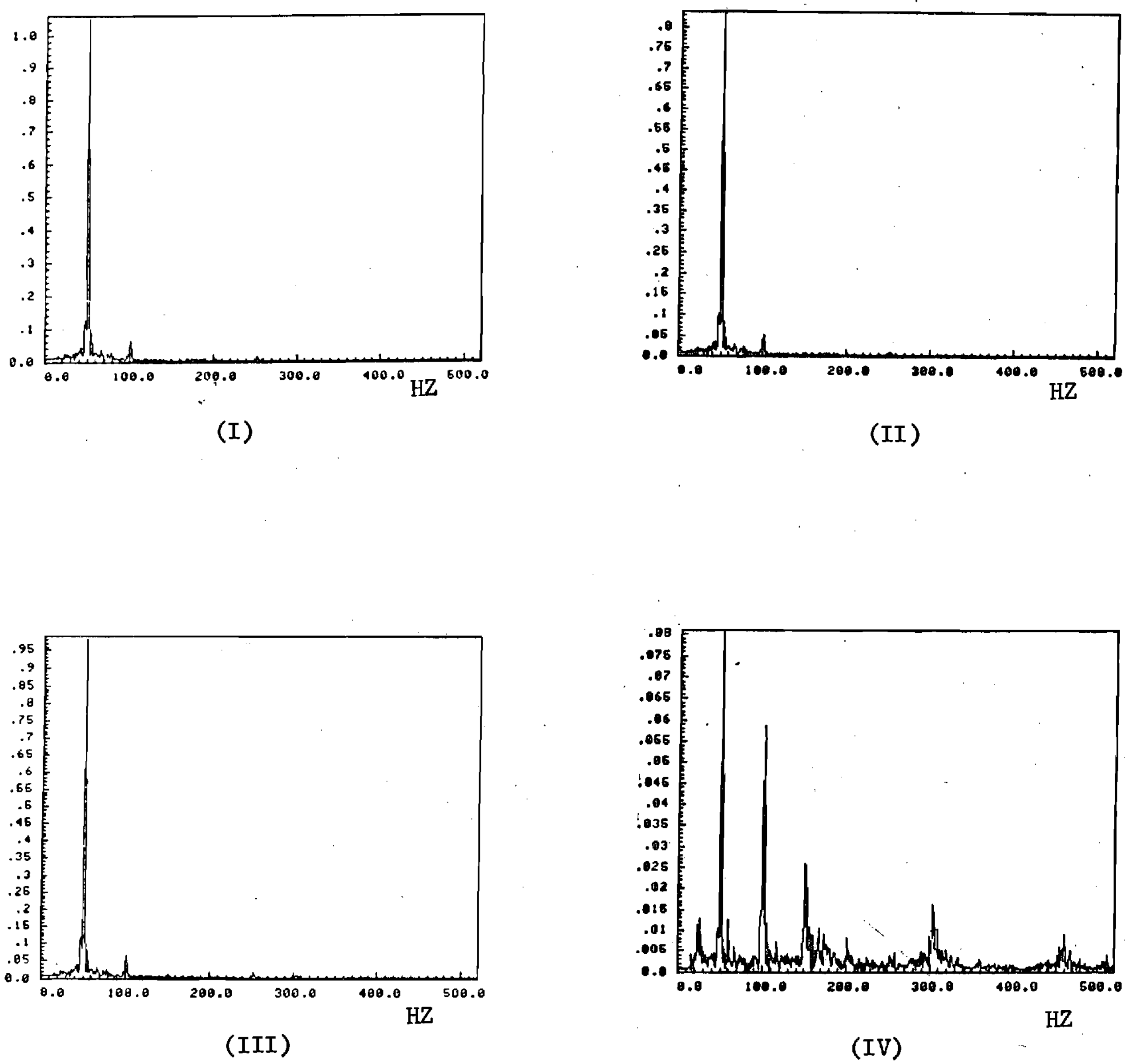


Figure 2a. Acoustic Pressure Spectra for Optimum Fuel/Air Ratio. (I) in Mixing Chamber, (II) in Combustion Chamber, (III) at the Head of Exhaust Pipe, (IV) at the Exit of Exhaust Pipe.

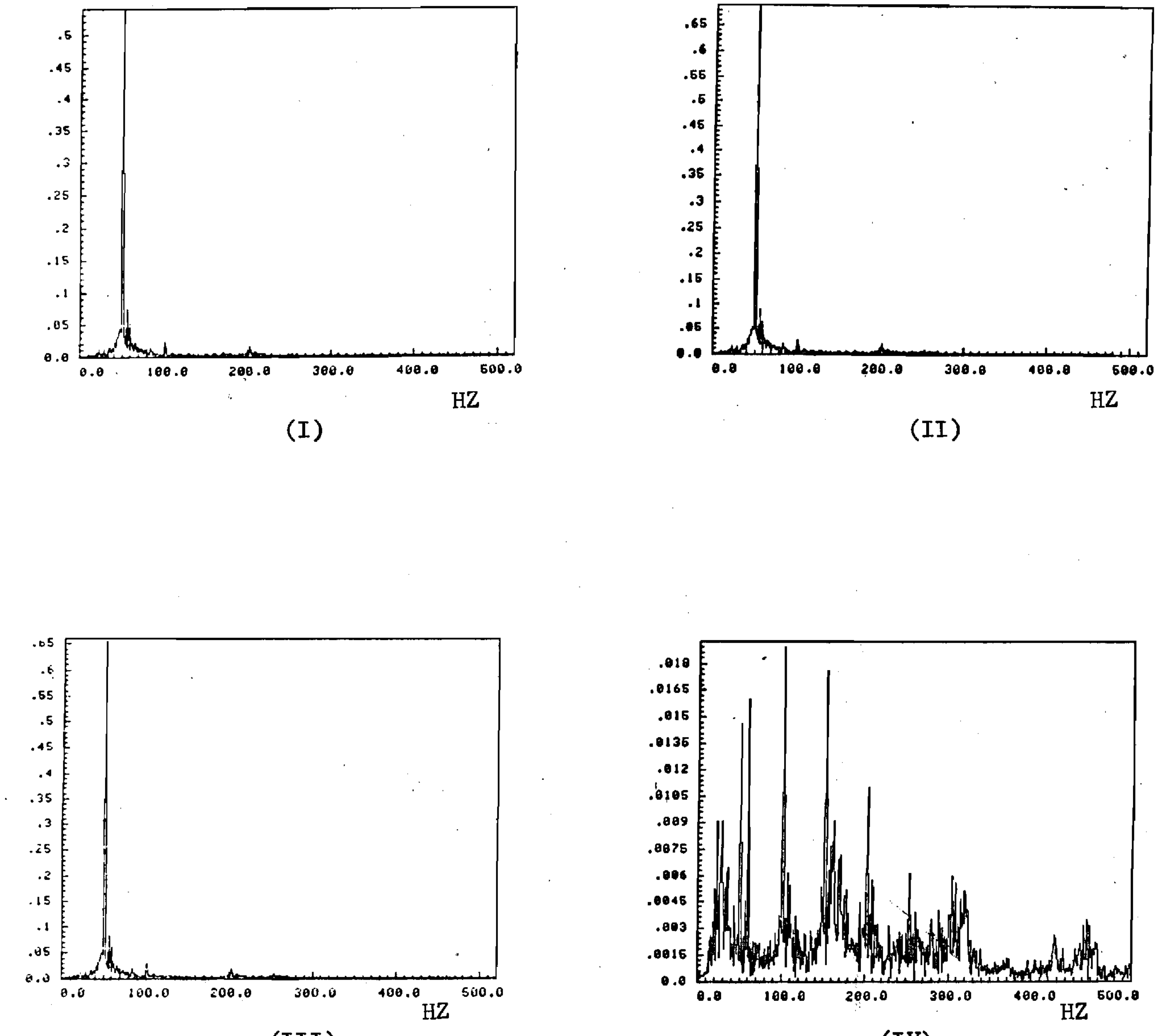


Figure 2b. Acoustic Pressure Spectra near Lean Limit of Operation. (1) in Mixing Chamber, (II) in Combustion Chamber, (III) at the Head of Exhaust Pipe, (IV) at the Exit of Exhaust Pipe.

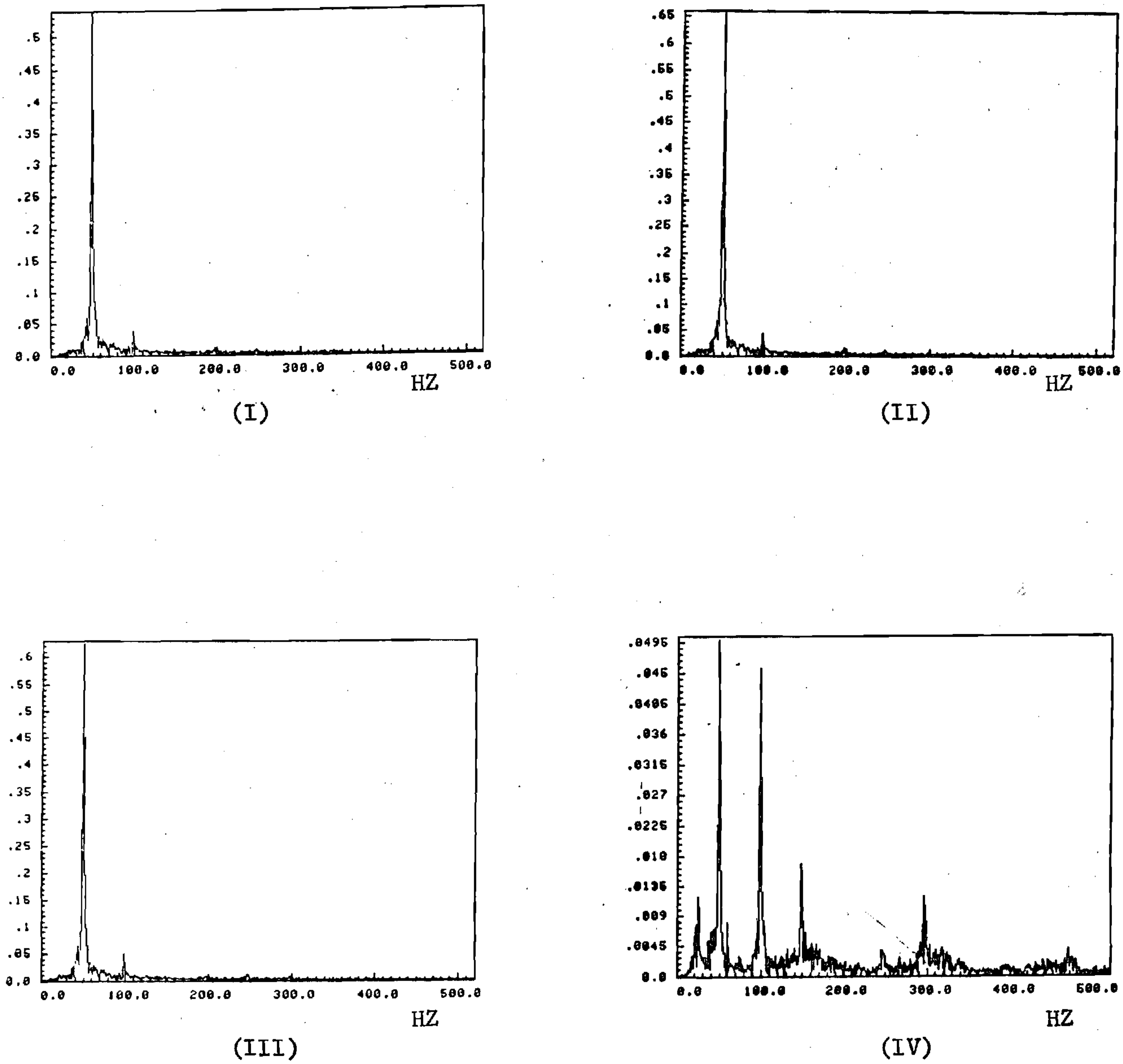


Figure 2c. Acoustic Pressure Spectra near Rich Limit of Operation. (I) in Mixing Chamber, (II) in Combustion Chamber, (III) at the Head of Exhaust Pipe, (IV) at the Exit of Exhaust Pipe.

E-16-662

Pulsating Burners - Controlling Mechanisms and Performance

Quarterly Report
March 1986 - May 1986

Prepared by

B. T. Zinn, B. R. Daniel and J. I. Jagoda

School of Aerospace Engineering
Georgia Institute of Technology

For

Gas Research Institute
Grant No. 5083-260-0873
GRI/85-0032

GRI Project Manager
James A. Kezerle
Combustion

June 10, 1986

GRI DISCLAIMER

LEGAL NOTICE: This report was prepared by the Georgia Institute of Technology as an account of work sponsored by the Gas Research Institute (GRI). Neither GRI, members of GRI, nor any person acting on behalf of either:

a. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

b. Assume any liability with respect to the use of, or for damages resulting from the use of, any information, apparatus, method, or process disclosed in this report.

RESEARCH SUMMARY

Title	Pulsating Burners - Controlling Mechanisms and Performance
Contractor	Georgia Tech Research Institute
Contract Number	GRI Grant 5083-260-0873
Report Period	March 1986 - May 1986 Quarterly Report
Principal Investigator	B. T. Zinn, B. R. Daniel and J. I. Jagoda
Objective	The objective of this study is to gain an understanding of the fundamental processes, such as mixing and cycle to cycle reignition, which control the operation of gas fired pulse combustors. An analytical model is to be developed which will provide a rational procedure for the design and scaling of these burners.
Technical Perspective	In spite of the fact that gas fired pulse combustors for home heating have now been on the market for a number of years, little is known about the physical and chemical processes which control the operation of these devices. Of particular interest are the mixing of fuel and air, cycle to cycle ignition and the nature of the flame propagation in the burner. Such information is necessary for improving the operational characteristics of existing pulsating combustors and for guidance in the development of new burners for increased capacity or novel applications. Furthermore, the acquired insight will

be used to guide the development of a theoretical model for predicting the behavior of pulsating combustors. The availability of such a model would permit the replacement of the costly empirical trial and error methods used to date for the design and scaling of pulsed combustors by a more rational approach.

Technical Approach

As a first step, a parametric study is being carried out using steel combustors in order to determine the influence of the combustor geometry and fuel air ratio on its performance and efficiency. Selected burners have been and are being fabricated in pyrex and quartz and their flow field investigated using high speed cinematography Schlieren/shadowgraphy, stream line and mixing visualizations as well as laser Doppler velocimetry (LDV). Lastly, C-H and C-C spectroscopy is being used in the determination of the timing, location and rate of heat release during the combustion cycle. A linear and, if necessary, a non-linear theoretical model of the combustor is being developed to provide a basis for future pulsating combustor design and scaling.

Program Plan:

The program is divided into three distinct tasks outlined below:

Task I - Experimental Investigation
- A Performance
- B Flow Visualization
  - a) streamline visualization
  - b) shadow/Schlieren
- C Mixing Visualization

D LDV

E C-H & C-C Spectroscopy

Task II - Analytical Study

Task III - Reporting

Results

During this reporting period the combustion chamber of the pulse combustor was thermally insulated, first externally and then internally. With external insulation the temperature in the combustor increased while the dB level remained unchanged. At the same time the range of operation of the pulse combustor increased somewhat, especially near the lean limit. When the combustion chamber was insulated internally, a further increase in the combustor temperature was observed. However, because of the absorption of acoustic energy in the insulating material the sound level in the combustor was reduced by 15 dB. In addition, the frequency of pulsations dropped from 47 to 39 Hz.

When the tail-pipe length of the uninsulated combustor was varied between 2" and 144", an increase in frequency with decreasing tail pipe length was noted. Operating at the lower frequency (i.e., with the longer tail pipe) extended the rich limit of operation of the combustor from an equivalence ratio of just over 1 obtained with the "standard" 74" tail pipe to a limiting fuel/air ratio of 1.43 for a tail pipe approximately twice as long. It is believed that the increased cycle duration at the lower combustor frequency provided sufficient time for the mixing and combustion processes to be completed for conditions outside the previously attained limits of operation. This conclusion is further supported by the observation that the limits of operation of the combustor can also be extended by pressurizing the air supply upstream of air valve which increases the air injection velocity and, thus, the mixing rate. When the combustor was run without a tail-pipe the frequency increased significantly while the dB level dropped to just over 130 dB. However, unless the air was supplied to its flapper valve under pressure the flame positioned itself at the exit of the combustion chamber.

The natural frequency of the combustor assembly was predicted by modeling the mixing and combustion chambers as a Helmholtz resonator and adding the effect of the wave motion in the tail pipe. For the cold case (without combustion) the predicted natural frequencies agreed to within 2% with the experimentally determined values. The analysis was then extended to cases with combustion. Again the combustor was modelled as a combination of Helmholtz resonator and oscillating tail pipe assuming an average velocity of sound based upon the mean temperature in the combustion chamber. The thus calculated frequencies of the pulsations agreed to within 8% with measured values over a wide variety of combustor geometries and operating conditions. The increases of frequency with decreasing combustor volume and decreasing equivalence ratio were, thus, correctly modeled.

INTRODUCTION

The objective of this study is to gain insight into the fundamental processes responsible for the operation of gas fired pulse combustors and to develop an analytical model capable of predicting the performance characteristics of new pulse combustor designs. Furthermore, the model considers the effect of scaling upon combustor performance. To this end, the effects of a number of geometrical combustor parameters, such as L/D ratio, combustor volume and exhaust pipe length as well as of operational parameters such as equivalence ratio, upon the combustor performance as evaluated from the exhaust gas composition, combustion efficiency, temperature distribution and dB level are under investigation. Also, the interactions between the pulsating flow field and combustion processes are being studied. Special emphasis is placed on determining the source and location of the cyclic ignition. The reactant injection and mixing, as determined by flow visualization, are being correlated with the pressure fluctuations and the fluctuations in the combustion intensity obtained from the emission spectroscopy of selected flame radicals. Velocities are measured using LDV. The influence of the operating conditions of the combustor, such as its pulse frequency, temperature and inlet pressure, on its limits of pulsed operation are being investigated. Pulse frequencies of the combustors are being predicted from the combustor geometries and measured mean flame temperatures. An analytical model is being developed which will predict the performance of combustors having different geometries and scales. The insights gained from the above experiments will be used in the development of the model which will, in turn, be tested against further experimental data. It is, thus, anticipated that this study will enable the industry to abandon the currently used empirical approach in the design and development of pulsed combustors in favor of a rational design procedure based upon dependable model predictions.

Program Plan

The program is divided into three major tasks as outlined below:

Task I - Experimental Investigation

A. Performance Evaluation. The performance of a number of combustors of different geometries (i.e., different L/D, volumes, tail pipe lengths, etc.) is being investigated using temperature, pressure and combustion efficiency measurements. For each configuration, the performance is evaluated over a range of air/fuel ratios and fuel loadings.

B. Flow Visualization. Stream lines are being investigated by recording the tracks of seed particles moving through a laser light sheet. This process is repeated with the laser sheet at different combustor locations. Refractive index gradients caused by the flame front or by pockets of hot and cold gases are visualized using Schlieren and shadowgraphy.

C. Mixing Visualization. Mixing patterns are being recorded photographically by heavily seeding either the fuel or the air and illuminating the transparent combustor using a laser light sheet. Again, the visualization is repeated with the laser sheet at different combustor locations. Alternative methods, for example using soot generated in the combustor are also being investigated.

D. LDV. A 2-D Laser Doppler Velocimeter has been set up and tested, and is used to measure velocities at selected stations in the mixing and combustion chamber and in the tail pipe. The data acquisition system previously developed is being modified to permit ensemble averaging over a number of cycles. A special combustor is being fabricated in order to avoid the problem of beam displacement due to the cylindrical walls.

E. C-H C-C and O-H Spectroscopy. In this part of the study radiation from the combustor is passed through the respective filters and its intensity measured using a photomultiplier. The radiation measurements are then related to combustion intensities. These are then compared with the phase measurements of mixing as determined from the high speed shadowgrams and with the instant of ignition as recorded using high speed, low sensitivity Schlieren.

Task II - Analytical Study

A theoretical model which describes the performance of the investigated combustors is being developed. The model will incorporate the findings of the experimental phases of the program. The model will be linear and investigate the possible range of operating conditions of the burners.

Task III - Reporting

As per contract agreement.

TECHNICAL PROGRESS AND RESULTS

During the past reporting period (March - May '86) the pulse combustor was operated with both its mixing and combustion chamber thermally insulated. At first, the mixing and combustion chamber were externally insulated. As expected, the insulation resulted in an increase in center line temperatures in the mixing and combustion chambers, with the increase being largest in the middle of the combustion chamber (see Table 1). At the same time the CO level in the exhaust increased by approximately 15% while the CO_2 level remained unaffected, as was the dB level. In addition, the range of equivalence ratios over which the combustor could be operated successfully was extended slightly, especially at the lean limit. The insulated combustor could be fired for fuel air ratios between .55 and 1.06. This compares with equivalence ratio limits of 0.65 and 1.04 respectively in the uninsulated combustor. Interestingly, careful examination of the data revealed that, in general, the combustor will only operate continuously for a prolonged period of time if the temperature near the upstream end of the combustion chamber, where the center-line temperature is maximum for all cases investigated, exceeds at least 1020^{o}C. A similar minimum required temperature for sustained combustion was also observed in an unrelated study, in which the lean limit of combustion was extended by preheating the reactants. Finally, after dismantling the insulated combustor scaling was observed near the center of the cylindrical wall of the combustion chamber. This indicates that while the maximum temperature along the center line is reached near the upstream end of the combustion, the maximum temperature near the walls occur near the middle of the combustion chamber.

In order to protect the combustor walls from the high temperatures inside the combustion chamber a second combustion chamber was insulated internally. The combustion chamber selected for this test was of larger diameter such that once the insulation material was added the internal diameter of the combustion chamber was equal to that used in the runs with external insulation. In this configuration even higher temperatures were reached in the combustion chamber (Table 1). However, because of the absorption in the insulating material the level of the pressure oscillations was reduced from 171 dB to 154 dB. Because of this reduction in the dB level, less reactants entered the combustor per cycle and it was necessary to increase the gap in the air flapper valve to maintain the pulsations. In addition, the frequency was reduced from 47 to 39 Hz in the internally insulated combustor.

Further tests were carried out on the uninsulated combustor by varying the length of the tail pipe. The exhaust decoupler was removed for these tests. Tail pipes of lengths of 2", 27", 73" (normal length), 100", 134" and 144" were tested. As expected, the frequency of pulsations decreased with increasing tail pipe length from 78 Hz for the 27" tail pipe to 29 Hz for the

144" length tail pipe (see Table II). However, for the short tail pipes the air upstream of the flapper valve had to be pressurized to about 5" of water pressure to maintain pulsating combustion at levels of approximately 165 dB, 6 dB lower than for the standard tail pipe. If the air pressure was reduced towards atmospheric pressure the combustor tended to operate in a continuous, non-pulsating mode. For the long tail pipe, on the other hand, strong pulsations were observed for atmospheric pressure upstream of the flapper valve. More importantly, the low pulsation frequencies extended the rich limit of operation to equivalence ratios of 1.43 for a tail pipe length of 144". It is hypothesized at this point, that the shorter cycles associated with the short tail pipe provide insufficient time for the fuel and air to mix and the combustion to be completed to a significant extent during one half of the period of the cycle, which is necessary for successful driving of the pulsation. This can be overcome by facilitating more rapid mixing through injecting the air stream under pressure. On the other hand, for the long cycle period, corresponding to the longer tail pipe, sufficient time is available to complete the mixing and combustion processes even for fuel-air ratios which lie outside the operating range of the combustor fitted with the standard tail pipe. Finally, for the combustor with only a 2" tail pipe the frequency increased to approximately 230 Hz although the sound levels were reduced to 130 dB. Furthermore, the flame tended to stabilize at the exhaust of the combustor for air supplied near atmospheric pressure and only flashed back into the combustor when the air supply pressure was increased.

In a separate part of the study, the natural frequencies of the individual components of the pulse combustor and their assemblies were calculated and compared with measured values. As a first step these comparisons were carried out in the absence of combustion separately for (1) the combustion chamber, (2) the combustion chamber plus mixing chamber and (3) the combustion chamber plus mixing chamber plus air valve assembly. Theoretically, all three configurations were treated as Helmholtz resonators having different volumes. Their natural frequencies were measured by blowing air across the exit plane of the combustor. For the first two configurations the theoretically and experimentally determined frequencies agreed to within 2%. Once the volume of the valve housing and of the pipe connecting it to the mixing chamber were added the discrepancy increased to 5% because of the complex shape of the valve assembly. As a next step the tail pipe without the decoupling chamber was added to the combustor and the natural frequency of the assembly was measured. This frequency was then calculated by analyzing the "combined" acoustics of the combustor and a of the tail pipe. Again, the predicted frequencies agreed with the measured values to within 2.5%.

This part of the study was then extended to the case with combustion. Once again the combustor plus tail pipe were represented by a Helmholtz resonator attached to a long tube. The volume of the Helmholtz resonator was set equal to the combined volume of the combustion and mixing chamber plus that of the air valve assembly while a mean speed of sound, based upon the measured mean temperature in the combustion chamber, was used. The analysis was applied to five different combustors all of different combustion chamber volume which had previously been studied for the dependence of their frequency upon the equivalence ratio. The model includes one correction factor which was determined by fitting the predicted frequency to that measured for one combustor at one equivalence ratio. This value for the correction factor was then kept constant for all combustors and all equivalence ratios. The thus predicted frequencies agreed with the measured frequencies to within 8% for all the combustors and equivalence ratios tested. As shown in Table III the decrease of frequency with increasing combustor volume was, thus, correctly predicted. A small increase in pulse frequency was observed when the equivalence ratio in the combustor was reduced. This trend was also well predicted as shown in Table IV.

WORK PLANNED

During the next reporting period further performance tests will be carried out for combustors of different tail pipe lengths including a combustor without a tail pipe. Air flapper valve settings and air supply pressures will be varied and frequencies, dB levels, operational limits and exhaust gas compositions for selected cases will be determined. Comparisons with predicted values of the pulse frequencies will be carried out. The construction of the new pulse combustor with flat windows for LDV, side on Schlieren and radiation measurements will be completed. A new detection system for spacially and temporally resolved C-C, C-H and O-H emission spectroscopy will be designed and constructed and the software will be adapted to phase lock the radiation and pressure signals. The possibility of developing a new technique for visualizing the mixing pattern such as the use of smoke generated in the combustor will be investigated. Work on the analytic model of the pulse combustor will also continue.

Table I

Comparison of Uninsulated, Externally and Internally Insulated Combustors

	Uninsulated	Externally Insulated	Internally Insulated
Equivalence ratio	.780	.780	.783
T_1^*	1106	1125	1154
T_2^*	1005	1027	1104
T_3^*	975	991	-
dB	170.3	171.5	154.3
Frequency	47	47	39

* T_1, T_2 amd T_3 are the center line temperatures in the upstream, the middle and the downstream sections of the combustion chamber respectively.

Table II

Effect of Tail Pipe Length on the Pulsations

L	Hz	dB
2"	230	130
27"	78	165
72"	50	171
100"	36	170
134"	30	167
144"	29	168

Table III

Comparison of Predicted and Measured Frequencies for Different Combustor Volumes with Combustion

Combustor Volume (in^3)	Predicted Frequency (Hz)	Measured Frequency (Hz)
97.6	58.8	54.5
183.2	47.4	45.0
185.8	47.4	45.5
199.7	45.9	43.0
296.2	39.0	39.5

Table IV

Comparison of Predicted and Measured Frequencies
for Different Equivalence Ratios with Combustion

Air Valve Setting	Predicted Frequency (Hz)	Measured Frequency (Hz)
.009"	46.3	42.5
.010"	47.7	43.5
.012"	47.4	45.0
.015"	49.3	45.5
.016	49.1	45.5
.017"	49.3	45.5

Increasing air valve setting corresponds to decreasing equivalence ratio.
Combustion chamber volume for this test: 183.2 in^3.

E-16-662

Pulsating Burners - Controlling Mechanisms and Performance

Quarterly Report

June 1986 - August 1986

Prepared by

B. T. Zinn, B. R. Daniel and J. I. Jagoda

School of Aerospace Engineering

Georgia Institute of Technology

For

Gas Research Institute

Grant No. 5083-260-0873

GRI/85-0032

GRI Project Manager

James A. Kezerle

Combustion

September 10, 1986

GRI DISCLAIMER

RESEARCH SUMMARY

Title	Pulsating Burners - Controlling Mechanisms and Performance
Contractor	Georgia Tech Research Institute
Contract Number	GRI Grant 5083-260-0873
Report Period	June 1986 - August 1986 Quarterly Report
Principal Investigator	B. T. Zinn, B. R. Daniel and J. I. Jagoda
Objective	The objective of this study is to gain an understanding of the fundamental processes, such as mixing and cycle to cycle reignition, which control the operation of gas fired pulse combustors. An analytical model is to be developed which will provide a rational procedure for the design and scaling of these burners.
Technical Perspective	In spite of the fact that gas fired pulse combustors for home heating have now been on the market for a number of years, little is known about the physical and chemical processes which control the operation of these devices. Of particular interest are the mixing of fuel and air, cycle to cycle ignition and the nature of the flame propagation in the burner. Such information is necessary for improving the operational characteristics of existing pulsating combustors and for guidance in the development of new burners for increased capacity or novel applications. Furthermore, the acquired insight will

be used to guide the development of a theoretical model for predicting the behavior of pulsating combustors. The availability of such a model would permit the replacement of the costly empirical trial and error methods used to date for the design and scaling of pulsed combustors by a more rational approach.

Technical Approach

As a first step, a parametric study is being carried out using steel combustors in order to determine the influence of the combustor geometry and fuel air ratio on its performance and efficiency. Selected burners have been fabricated in pyrex and quartz. Their flow fields are being investigated using high speed cinematography Schlieren/shadowgraphy, stream line and mixing visualizations as well as laser Doppler velocimetry (LDV). Lastly, C-H and C-C spectroscopy is being used in the determination of the timing, location and rate of heat release during the combustion cycle. A linear and, if necessary, a non-linear theoretical model of the combustor is being developed to provide a basis for future pulsating combustor design and scaling.

Program Plan:

The program is divided into three distinct tasks outlined below:

Task I - Experimental Investigation

- A Performance
- B Flow Visualization
  - a) streamline visualization
  - b) shadow/Schlieren
- C Mixing Visualization

D LDV

E C-H & C-C Spectroscopy

Task II - Analytical Study

Task III - Reporting

<u>Results</u>

During this reporting period the fabrication of the combustor with flat, transparent side and end walls in the mixing and combustion chambers has been completed. This combustor will be used for the side-on Schlieren, improved flow and mixing visualizations and LDV studies.

Tests were performed using the steel combustor in which the driving and damping characteristics of the pulse combustor were investigated by monitoring the exponential growth and decay of the acoustic pressure amplitudes during start up and shut down of the combustor. From these growth and decay rates a measure of the driving and damping by the combustor in the form of a driving and damping factors were determined. Since the operation of the spark plug interfered with the exponential growth of the pressure amplitudes, the combustor was, at first, operated at very low pulsation amplitudes using small amounts of fuel which by passed the fuel solenoid valve. This valve was then opened and closed and the exponential pressure amplitude growth and decay rates were observed. From these the driving and damping factors were calculated for different operating conditions.

Detailed analysis of the previously obtained high speed Schlieren movies had indicated that the fuel enters the mixing chamber at a time at which the pressure in the mixing chamber is still higher than the pressure at which the fuel is supplied. Acoustic pressure measurements were, therefore, carried out simultaneously in the combustor and in the duct which connects the fuel flapper valve to the mixing chamber. The results thus obtained show the existence of considerable acoustic pressure fluctuations in the fuel supply duct upstream of the mixing chamber which slightly lag those in the combustor. Thus the pressure maximum in the mixing chamber duct occurs before the pressure maximum in the fuel supply duct. Immediately following the pressure maxima the pressure in the fuel supply duct is, therefore, higher than that in the mixing chamber and remains higher until the pressures begin to rise again. This pressure differential is responsible for the early appearance of the jet from the fuel pipe into the mixing chamber. It, therefore, appears that the acoustics in the fuel duct play an important role in the timing of the injection of the reactants.

As reported in the last quarterly report, shortening the combustor (e.g., 29") produced higher pulsation frequencies However, these combustors operated in the pulsating mode only if the air upstream of the flapper valve was pressurized. The ranges of air pressure over which the combustor could be operated in the pulsating mode was determined for different air valve settings, and thus different fuel/air ratios. This "operational envelope" indicated that as the air valve opening increases, the air pressure required for pulsed operation decreases. Furthermore, the operational envelope was found to be widest for a valve setting of .012". For all conditions for which pulse combustion operation could be obtained the combustion efficiency was well over 99.5% although the detected CO levels detected were slightly higher for higher fuel/air ratios where higher air pressures were required for successful operation.

Finally, a radiation measurement system with some spacial as well as good temporal resolution has been designed assembled and tested.

INTRODUCTION

The objective of this study is to gain insight into the fundamental processes responsible for the operation of gas fired pulse combustors and to develop an analytical model capable of predicting the performance characteristics of new pulse combustor designs. Furthermore, the model considers the effect of scaling upon combustor performance. To this end, the effects of a number of geometrical combustor parameters, such as L/D ratio, combustor volume and exhaust pipe length as well as of operational parameters such as equivalence ratio, and air supply pressure upon the combustor performance as evaluated from the exhaust gas composition combustion, efficiency, temperature distribution and dB level are under investigation. Also, the interactions between the pulsating flow field and combustion processes are being studied. Special emphasis is placed on determining the source and location of the cyclic ignition. The reactant injection and mixing, as determined by flow visualization, are being correlated with the pressure fluctuations and the fluctuations in the combustion intensity obtained from the emission spectroscopy of selected flame radicals. Velocities are measured using LDV. The influence of the operating conditions of the combustor, such as its pulse frequency, temperature and inlet pressure, on its limits of pulsed operation are being investigated. Pulse frequencies of the combustors are being predicted from the combustor geometries and measured mean flame temperatures. An analytical model is being developed which will predict the performance of combustors having different geometries and scales. The insights gained from the above experiments will be used in the development of the model which will, in turn, be tested against further experimental data. It is, thus, anticipated that this study will enable the industry to abandon the currently used empirical approach in the design and development of pulsed combustors in favor of a rational design procedure based upon dependable model predictions.

Program Plan

The program is divided into three major tasks as outlined below:

Task I - Experimental Investigation

A. Performance Evaluation. The performance of a number of combustors of different geometries (i.e., different L/D, volumes, tail pipe lengths, etc.) is being investigated using temperature, pressure and combustion efficiency measurements. For each configuration, the performance is evaluated over a range of air/fuel ratios and upstream air pressures. In addition the driving and damping characteristics are determined by measuring the rate of growth and decay of the pressure amplitudes during the start up and shut down phases.

B. Flow Visualization. Stream lines have been investigated by recording the tracks of seed particles moving through a laser light sheet. This process was repeated with the laser sheet at different combustor locations. However, because the curved combustor walls caused part of the light in the beam to be refracted out of the test region, the images were not as clear as anticipated. These tests will, therefore, be repeated using the pulse combustor with flat, transparent side walls. Refractive index gradients caused by the flame front or by pockets of hot and cold gases, on the other hand, have been very successfully visualized using Schlieren and shadowgraphy.

C. Mixing Visualization. It was attempted to record mixing patterns photographically by heavily seeding either the fuel or the air and illuminating the transparent combustor using a laser light sheet. However, because of the low light levels which could penetrate the cylindrical combustor walls this technique was not successful for this combustor configuration. However, alternative methods such as using soot generated in the combustor will be investigated using the flat walled combustor.

D. LDV. A 2-D Laser Doppler Velocimeter has been set up and tested, and is used to measure velocities at selected stations in the mixing and combustion chamber and in the tail pipe. A previously developed data acquisition system is being modified to permit ensemble averaging over a number of cycles. A special combustor is being fabricated in order to avoid the problem of beam displacement due to the cylindrical walls.

E. C-H C-C and O-H Spectroscopy. In this part of the study radiation from the combustor is passed through the respective filters and its intensity measured using a photomultiplier. The radiation measurements are then related to combustion intensities. These are then compared with the phase measurements of mixing as determined from the high speed shadowgrams and with the instant of ignition as recorded using high speed, low sensitivity Schlieren.

Task II - Analytical Study

Work proceeds on the development of a theoretical model capable of predicting the performance of the investigated combustors. A perturbation solution approach is used and solutions up to second order in the amplitude of the pulsations are sought. Special emphasis is being given to developing a capability for predicting the dependence of the combustor behavior upon the valve dynamics.

Task III - Reporting

As per contract agreement.

TECHNICAL PROGRESS AND RESULTS

During the past reporting period the driving and damping characteristics of the pulse combustor were investigated by monitoring the exponential growth and decay rates of the acoustic pressure amplitudes during start up and shut down of the combustor. This study has been undertaken, because a simplified analysis has shown that the difference between such growth and decay rates provides a measure of the driving of pulsations by the combustion process. During these transients the time dependence of the pressure amplitude, is described by $p \propto e^{\alpha t}$ where α equals the difference between the driving and the damping processes during the start up phase, and only the damping process during shut down. In order to determine these driving and damping factors, the acoustic pressure - time traces were recorded during the start up and shut down phases of the combustor (Figs. 1a & b). In practice, the combustor was shut down by closing a fast acting solenoid valve located just upstream of the fuel flapper while the decay in pressure amplitude was recorded. Normal ignition procedures could not, however, be used to measure the amplitude growth rate because the spark plug operation interfered with the exponential growth of the pulsations. The growth rate was, therefore, determined by, at first, operating the combustor at very low pulsation amplitudes using small amounts of fuel which was allowed to bypass the solenoid valve. When the latter was suddenly opened, the fuel flow rate was abruptly increased causing an exponential growth in the pressure fluctuations which was recorded. Although the growth or decay periods only lasted 3-4 cycles because of the low frequencies of the combustor, the plots of ln p versus t, for these time intervals, provided straight lines (Fig. 2a & b). From the slopes of these lines the damping and driving factors were determined.

Tests with several different fuel/air ratios have been carried out and the results are currently being analyzed. In addition, when a steel wool plug was placed inside the downstream section of the exhaust pipe just upstream of the decoupling chamber, no change in the driving factor was observed. However, as expected, a significant increase in the damping factor was measured.

Detailed analysis of the high speed Schlieren movies obtained previously indicated, that the fuel begins to enter the mixing chamber very shortly after the combustor pressure has passed through its maximum at an instant when the mixing chamber pressure is still considerably above the 5 inch water pressure which was set in the fuel line. This suggested that the acoustic properties of the pipe leading from the fuel flapper valve to the mixing chamber may be important. Therefore, acoustic pressure measurements were carried out simultaneously, in the fuel supply pipe and in the mixing chamber. The results thus obtained (Fig. 3) show the existence of acoustic pressure oscillations in the fuel duct which reach almost the same maximum amplitudes as those in the combustor. In contrast, the minimum pressures in the duct only reaches one fifth of the value of the minimum of the pressures amplitudes in the combustor. This may be due to the fact that while the combustion products depart the combustor, causing a reduction in pressure, new fuel enters the fuel supply duct through the now open flapper valve keeping the latter at a higher pressure. Furthermore, the pressure fluctuations in the mixing chamber were observed to slightly lead the pressure oscillations in the fuel supply duct. The observed lead time corresponds to the time at which the first gas jet was observed to enter the mixing chamber from the fuel supply duct. It, therefore, appears that the acoustics of the fuel supply duct play an important role in the timing of the injection of the reactants and, consequently, the operation of the pulse combustor.

As previously reported, the frequency of the pulse combustor can be considerably increased by shortening its tail pipe. It has also been found that in this case the combustor will operate in a pulsating mode only if the air upstream of its valve is pressurized. The ranges of air pressure over which the combustor could be operated in the pulsating mode was determined for a combustor fitted with a 29" long tail pipe for different air valve settings. Upper and lower operational limits of the air pressures for three different air valve settings and their corresponding excess air values are shown in Fig. 4. Clearly, a larger air valve opening requires a smaller air pressure for pulse operation. In fact, for an air flapper valve setting of .02" pulse combustion could be obtained with no air pressurization. Furthermore, the "operational envelope" was found to be widest at a valve setting of .012". However, for no one air pressure could the combustor be successfully operated at all air valve settings. For all conditions for which pulse combustion operation could be obtained the combustion efficiency was well over 99.5%. However, the detected CO levels were slightly higher for higher fuel/air ratios where air pressures above 6" were required for successful pulse combustion operation. The dB level for a given fuel/air ratio was not affected by the air pressure-air valve setting combination chosen to achieve the equivalence ratio.

The fabrication of the combustor with flat, transparent side and end walls in the mixing and combustion chambers was completed. This combustor, which will be used for the side-on Schlieren, for improved flow and mixing visualization and for the LDV measurements is currently being tested. Finally, a radiation detection system for spontaneous OH, CH and CC emission from the flame zone of the combustor with some spacial as well as good temporal visualization was designed, assembled and tested. It consists of a photomultiplier tube, sensitive down to 300 nm, and fitted with a system of apertures to prevent all but a thin pencil of light originating at a given part of the flame from reaching the photodetector. The output from the PM tube is amplified, digitized and stored in a computer along with the outputs from the pressure probes. It will, then, be possible to determine the phase behavior between the heat release and the pressure fluctuations at different locations in the combustor.

WORK PLANNED

During the next reporting period the new combustor with the flat, transparent side and end walls will undergo thorough testing. OH, CH and CC radiation measurements with spacial resolution will be carried out simultaneously with the recording of the pressure fluctuations for a number of equivalence ratios. These results are expected to provide information about the locations of the ignition of the fresh charges in each cycle and the nature of the flame spread. In addition, the work on evaluating the damping and driving characteristics of the combustor will continue. Preparation will also be finalized for the LDV measurements in the pulse combustor and initial measurements should be undertaken. Finally, work on the analytic model of the pulse combustor will continue.

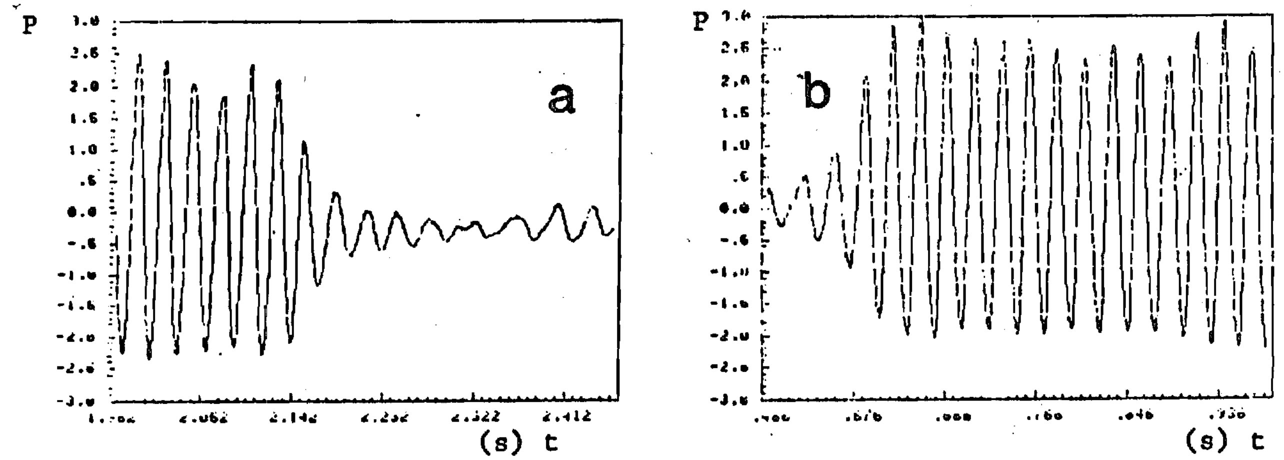


Figure 1: Pressure-time trace during (a) shut off, (b) start up.

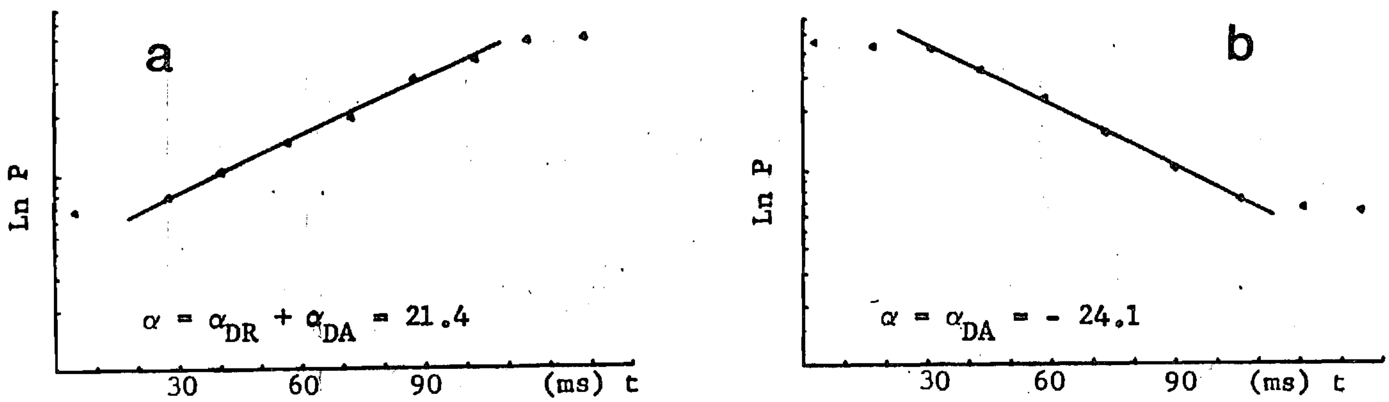


Figure 2: LnP vs. time during (a) start up, (b) shut off.

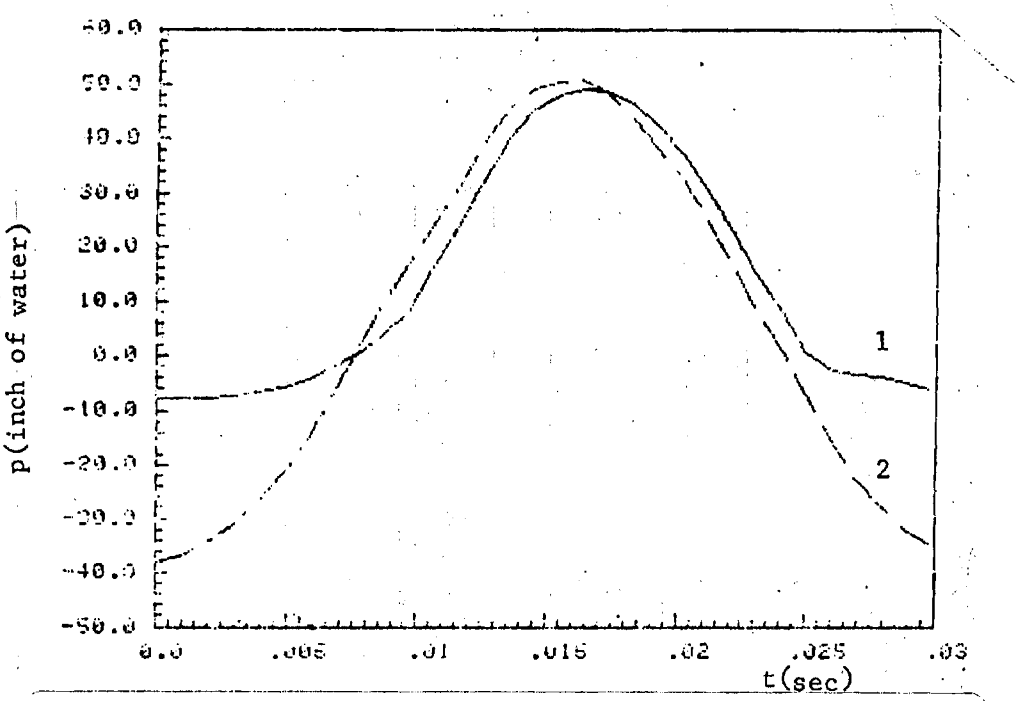


Figure 3: Pressure Fluctuations in (1) fuel supply line, (2) combustor.

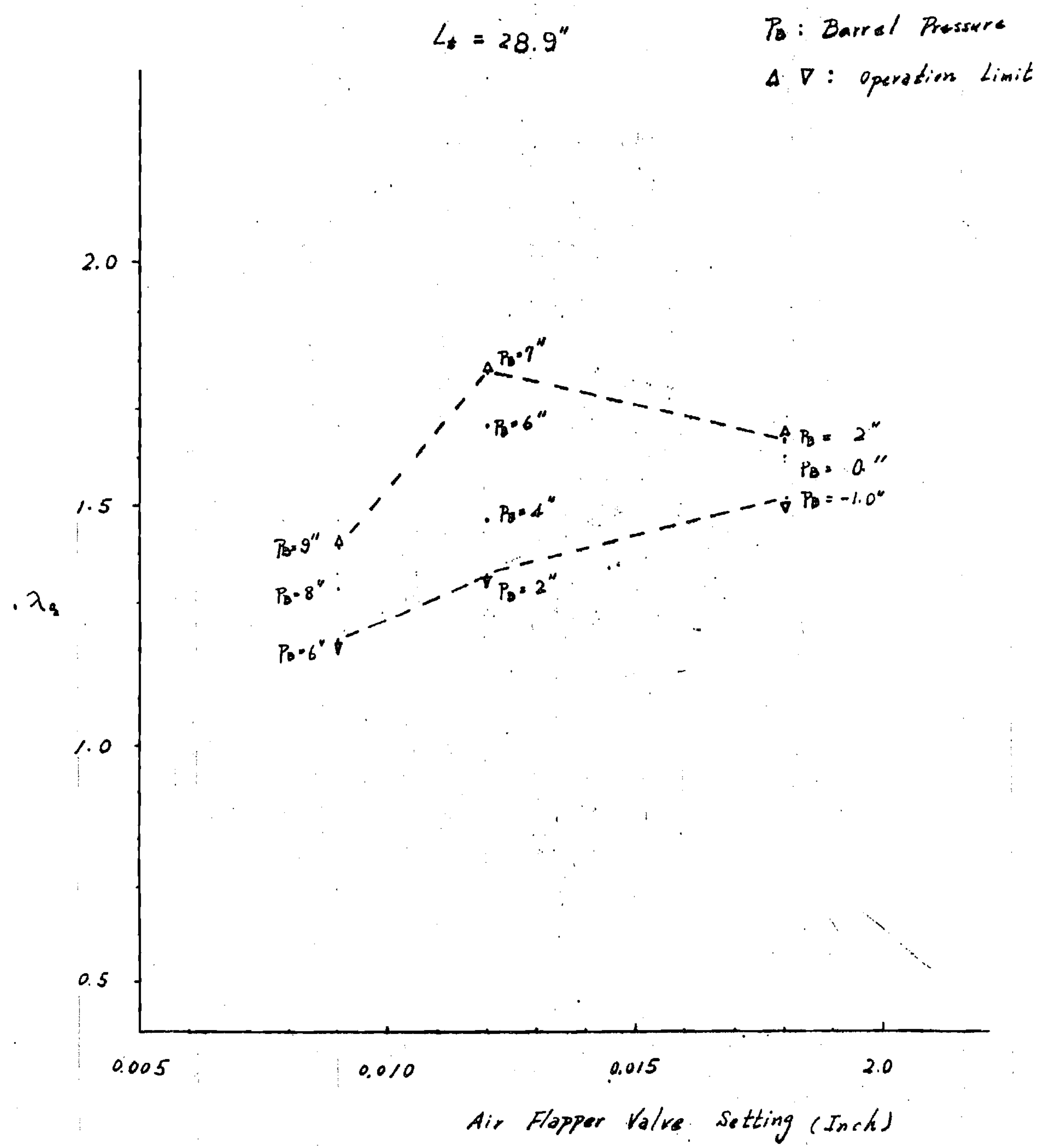


Figure 4: Operational air pressure limits of pulse combustor at different air flapper valve settings and corresponding air/fuel ratios (λ)

E-16-662

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
AEROSPACE ENGINEERING

404-894-3000

DANIEL GUGGENHEIM SCHOOL
OF AERONAUTICS

January 28, 1986

Mr. James A. Kezerle
Gas Research Institute
8600 West Bryn Mawr Avenue
Chicago, IL 60631

Dear Jim:

Enclosed please find a copy of our draft Annual Report. Please excuse the delay which was, in part, caused by the fact that we were submitting a number of papers to the 21st International Symposium on Combustion.

We hope that you will find the enclosed document suitable. Please feel free to make any changes necessary.

We look forward to hearing from you.

Yours sincerely,

J. Jagoda
Associate Professor

JJ/jj

Encl:

Pulsating Burners - Controlling Mechanisms and Performance

Annual Report
December 1, 1984 - November 30, 1985

Prepared by

B. T. Zinn, B. R. Daniel and J. I. Jagoda

School of Aerospace Engineering
Georgia Institute of Technology

For

Gas Research Institute
Grant No. 5083-260-0873
GRI/85-0032

GRI Project Manager
James A. Kezerle
Combustion

January, 1986

GRI DISCLAIMER

72-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. GRI 185-0032	2.	3. Recipient's Accession No.

Title and Subtitle

Pulsating Burners - Controlling Mechanism and Performance

5. Report Date

6.

Author(s)

B. T. Zinn, B. R. Daniel and J. I. Jagoda

8. Performing Organization Rept. No.

Performing Organization Name and Address

School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332

10. Project/Task/Work Unit No. E-16-662

11. Contract(C) or Grant(G) No.
(C) 5083-260-0873
(G)

Sponsoring Organization Name and Address

Gas Research Institute
8600 West Bryn Mawr Ave.
Chicago, IL 60631

13. Type of Report & Period Covered
Annual
Dec 1, 84 - Nov 30, 85

14.

Supplementary Notes

Abstract

Although gas fired pulsed combustors for home heating have now been on the marker for a number of years, little is known about the physical and chemical processes which control the operation of these devices. It is the objective of this study to gain an understanding of these processes such as mixing, cycle to cycle reignition and flame propagation in the burner. Such an understanding would permit a more rational approach towards the design of future combustors. Eleven combustors with different length, diameters and volumes have been constructed and tested. Mean temperatures and acoustic pressures were recorded and the exhaust gases analyzed for concentrations of CO_2, CO, O_2 and NO_x. All combustors performed well for fuel-air ratios between .6 and 1.1. This included one combustor in which the step between the mixing and combustion chambers was eliminated. The combustion chamber length and diameter had no influence on the combustor characteristics as long as the combustor volume remained fixed. An increase in volume, on the other hand, caused the frequency and dB levels of the pulsations and the mean temperatures to decrease. The combustion efficiencies for all combustors was very close to 100% except near the rich limit which appears to be mixing controlled. The CO and NO_x concentrations in the exhaust were of the order of 30-50 ppm for all combustors tested.

Document Analysis a. Descriptors

Pulse Combustor

b. Identifiers/Open-Ended Terms

Mixing, Reignition, Visualization, Radiation Measurements, Performance

c. COSATI Field/Group

Combustion

Availability Statement:	19. Security Class (This Report) Unclassified	21. No. of Pages
	20. Security Class (This Page) Unclassified	22. Price

(ANSI-Z39.18) See Instructions on Reverse

OPTIONAL FORM 272 (4-77)
(Formerly NTIS-35)
Department of Commerce

RESEARCH SUMMARY

Title	Pulsating Burners - Controlling Mechanisms and Performance
Contractor	Georgia Tech Research Institute
Contract Number	GRI Grant 5083-260-0873
Report Period	December 1984 - November 1985 Annual Report
Principal Investigator	B. T. Zinn, B. R. Daniel and J. I. Jagoda
Objective	The objective of this study is to gain an understanding of the fundamental processes, such as mixing and cycle to cycle reignition, which control the operation of gas fired pulse combustors. An analytical model is to be developed which will provide a rational procedure for the design and scaling of these burners.
Technical Perspective	In spite of the fact that gas fired pulse combustors for home heating have now been on the market for a number of years, little is known about the physical and chemical processes which control the operation of these devices. Of particular interest are the mixing of fuel and air, cycle to cycle ignition and the nature of the flame propagation in the burner. Such information is necessary for improving the operational characteristics of existing pulsating combustors and for guidance in the development of new burners for increased capacity or novel applications. Furthermore, the acquired insight will

be used to guide the development of a theoretical model for predicting the behavior of pulsating combustors. The availability of such a model would permit the replacement of the costly empirical trial and error methods used to date for the design and scaling of pulsed combustors by a more rational approach.

<u>Results</u>

During this contract year detailed performance measurements were carried out for different combustors in order to determine the effect of the fuel/air ratios (Φ) and various combustor dimensions on the operation of the pulse combustor. All combustors operated well for Φ's between about .6 and 1.1. The lower limit is close to the limit of flammability of the methane-air mixture while the upper limit seems mixing controlled. The pulse frequency is independent of Φ while the dB level is maximized at stoichiometric. The mean axial temperature distribution, which reaches its maximum near the mixing to combustion chamber transition, increases with Φ.

Combustion chamber diameters and lengths do not significantly affect the combustor performance. However, an increase in combustor volume results in a reduction in pulsating frequency and dB level indicating that the combustor behaves as a Helmholtz resonator. The influence of the combustor volume on the dB level also resulted in higher fuel and air flow rates for given value settings in the smaller combustor. The acoustic pressure oscillations are characterized by constant frequencies and some cycle to cycle variations in amplitude.

Coordination between shadowgrams and radiation measurements confirmed previous Schlieren results that "cycle to cycle" ignition occurs immediately after the fuel and air jets impinge upon one another. High speed shadowgrams near the limits of the combustor operation revealed significant differences in the timing of the fuel and air injection and mixing compared to the combustor operations under optimal conditions.

Technical Approach

As a first step, a parametric study is being carried out using steel combustors in order to determine the influence of the combustor geometry and fuel air ratio on its performance and efficiency. Selected burners have been and are being fabricated in pyrex and quartz and their flow field investigated using high speed cinematography Schlieren/shadowgraphy, stream line and mixing visualizations as well as laser Doppler velocimetry (LDV). Lastly, C-H and C-C spectroscopy is being used in the determination of the timing, location and rate of heat release during the combustion cycle. A linear and, if necessary, a non-linear theoretical model of the combustor is being developed to provide a basis for future pulsating combustor design and scaling.

Program Plan:

The program is divided into three distinct tasks outlined below:

Task I - Experimental Investigation

- A Performance
- B Flow Visualization
  - a) streamline visualization
  - b) shadow/Schlieren
- C Mixing Visualization

C LDV

E C-H & C-C Spectroscopy

Task II - Analytical Study

Task III - Reporting

INTRODUCTION

The objective of this study is to gain insight into the fundamental processes responsible for the operation of gas fired pulsed combustors and to develop an analytical model capable of predicting the performance characteristics of new pulsed combustor designs. Furthermore, the model will consider the effect of scaling upon combustor performance. To this end, the effects of a number of geometrical combustor parameters, such as L/D ratio, combustor volume and exhaust pipe length and diameter, upon the combustor performance are under investigation. Also, the interactions between the pulsed flow field and combustion processes are being studied. Special emphasis is placed on determining the source and location of the cyclic ignition and following the flame spread in the combustor. The streamlines in the flow field and the mixing of fuel and air are being visualized and recorded. Velocities are measured using LDV. An analytical model is being developed which will predict the performance of combustors having different geometries and scales. The insights gained from the above experiments will be used in the development of the model which will, in turn, be tested against further experimental data. It is, thus, anticipated that this study will enable the industry to abandon the currently used empirical approach in the design and development of pulsed combustors in favor of a rational design procedure based upon dependable model predictions.

Program Plan

The program is divided into three major tasks as outlined below:

Task I - Experimental Investigation

A. Performance Evaluation. The performance of a number of combustors of different geometries (i.e., different L/D, volumes, tail pipe lengths, etc.) is being investigated using temperature, pressure and combustion efficiency measurements.

For each configuration, the performance is evaluated over a range of air/fuel ratios and fuel loadings.

B. High Speed Cinematography. This technique is used to determine the locations of cycle to cycle ignition and the shape and motion of the flame.

C. Flow Visualization. Stream lines are being investigated by recording the tracks of seed particles moving through a laser light sheet. This process is repeated with the laser sheet at different combustor locations. Refractive index gradients caused by the flame front or by pockets of hot and cold gases are visualized using Schlieren and shadowgraphy.

D. Mixing Visualization. Mixing patterns are being recorded photographically by heavily seeding either the fuel or the air and illuminating the transparent combustor using a laser light sheet. Again, the visualization is repeated with the laser sheet at different combustor locations.

E. LDV. A 2-D Laser Doppler Velocimeter has been set up and tested, and is used to measure velocities at selected stations in the mixing and combustion chamber and in the tail pipe. The data acquisition system previously developed is being modified to permit ensemble averaging over a number of cycles. A special combustor is being fabricated in order to avoid the problem of beam displacement due to the cylindrical walls.

F. C-H & C-C Spectroscopy. In this part of the study radiation from the combustor is passed through the respective filters and its intensity measured using a photomultiplier. The radiation measurements are then related to combustion intensities. These are then compared with the phase measurements of mixing as determined from the high speed shadowgrams and with the instant of ignition as recorded using high speed, low sensitivity Schlieren.

Task II - Analytical Study

A theoretical model which describes the performance of the investigated combustors is being developed. The model will incorporate the findings of the experimental phases of the program. The model will be linear and investigate the possible range of operating conditions of the burners.

Task III - Reporting

As per contract agreement.

PROGRESS AND RESULTS FROM PREVIOUS YEAR

During the previous year (Dec. '83 - Nov. '84) 10 steel combustors having different lengths, lengths to diameter ratios, diameters and volumes were designed and fabricated. The 10 combustors' geometries were chose to allow the investigation of the effect of the diameter the length and the volume of the combustion chamber on the performance of the pulse combustor system. In addition, one combustor with transparent quartz end plates and one all pyrex combustor for optical diagnostics were constructed. An exhaust gas train to determine the combustion product compositions and, thus, the combustion efficiencies and the concentrations of exhaust pollutants was designed and set up. A scheme for determining the combustion efficiencies from the exhaust gas analysis was developed and software was written to acquire temperatures, acoustic pressures and exhaust gas compositions and to determine the efficiencies of the combustors.

The optics for measuring C-C and C-H radiation and a high speed Schlieren and shadowgraphy system had been placed in operation as had a particle track visualization system.

All the combustors operated well. The frequency of pulsation was found to be a function of the volume of the combustion chamber indicating that the combustors operate as Helmholtz resonators. Visual observations in the all pyrex combustor showed that for this configuration most of the combustion actually takes place in the "mixing chamber". High speed Schlieren and shadowgrams visualized the incoming fuel and air jets, their mixing and combustion. Low sensitivity Schlieren was used to differentiate between the Schlieren markings due to hot/cold gas interfaces and those due to flame fronts. C-H and C-C radiation from the entire combustor were measured near the fuel rich and fuel lean limits and for the optimum operating conditions of the combustor. The latter corresponds to those used in the visualization studies. These measurements showed that the reaction does not cease at any time during a cycle of operation. Furthermore, it was observed that the magnitudes of the radiation fluctuations decreased as the fuel air ratio is increased. At the same time, the pressure amplitudes remained essentially unchanged. Finally, comparison of the shadowgram and radiation measurements indicated that both C-C and C-H radiation sharply increase at the instant in each cycle at which the new fuel and air jets first impinge. This suggests that the ignition of the new charges occurs at this instant.

PROGRESS AND RESULTS OBTAINED IN CURRENT YEAR

During the current year of a the project (Dec. '84 - Nov. '85) both performance testing and optical diagnostics on the pulse combustor were continued. A large decoupling chamber was added upstream of the air valve of the steel combustors. This permits the measurement of the mean air flow rates for comparison with the flow rates calculated from the exhaust gas analysis. An eleventh steel combustor whose mixing and combustion chamber diameters are the same was designed and constructed. In this combustor the step between the mixing and combustion chamber was effectively eliminated. A sample probe was fitted to the exhaust pipe of the steel combustor one quarter of the way between the combustion chamber and the decoupler (Fig. 1). The probe was connected via a heated line to the exhaust gas sample train. The CO, CO_2, O_2 and NO_x analyzers in the sample train were calibrated and the data reduction software used to calculate the combustion efficiency was thoroughly tested. The combustors were instrumented with thermocouples and pressure transducers mounted in an infinite tube configurations to determine mean temperatures and acoustic pressures at various locations in the steel combustors (Fig. 1). The combustor mean boost pressure was also determined.

The stepless combustor described above worked well and exhibited the same characteristics as a combustor of equal volume, but with a step. This suggests that the step does not significantly influence the combustion process. All eleven combustors were found to operate well with their frequency of pulsation being dependent only on the combustor volume for fixed mixing chamber and exhaust line dimensions. Detailed tests were carried out for combustors of different dimensions which were selected to permit the determination of the influence of combustion chamber length, diameter and volume on the combustor performance. During these tests temperatures and pressures were measured at various locations in the mixing chamber, the combustion chamber, the exhaust pipe and the decoupler (Fig. 1). Fuel and air flow rates were measured upstream of the flapper valves. At the same time, the concentrations of CO, CO_2, O_2 and NO_x in the exhaust gas were measured. From these the combustion efficiencies and fuel equivalence ratios were calculated. The latter were compared with the values for the equivalence ratio obtained from the fuel and air flow rate measurements. They agreed, generally, to within 1-2%. The range of operation of each tested combustor was established by varying the air flapper valve setting since the fuel flapper setting is fixed. As the air flapper gap was increased the air flow rate increased considerably. At the same time the fuel flow rate decreased slightly despite the fixed fuel valve setting (Fig. 2).

All combustors operated well at nondimensional fuel air ratios (Φ) between slightly rich of stoichiometric and about .6. While the lean limit of operation of the combustors lies close to the limit of flammability of a methane-air mixture the fact that the combustor does not operate well on the rich side of stoichiometric was thought to be due to either inadequate mixing or to problems in the air flapper valve. Since the fuel flapper valve setting is fixed, the air flow had to be reduced to yield a fuel rich mixture in the mixing chamber. This required the setting of a very small gap in which the flapper disc could move, which could result in significant pressure losses in the air valve. To overcome this the effective cross-section of the flapper was reduced by plugging some of the holes in the air intake, resulting in a wider gap setting for low air flow rates. These changes, however, did not significantly extend the operational limits of the combustor. The limit slightly rich of stoichiometric seems, thus, to be mixing controlled.

Very good performance was achieved for all conditions except near the operational limits. The frequencies of oscillation were independent of Φ (Fig. 3) while the dB levels increased slightly as Φ increased and then decreased somewhat near stoichiometric (Fig. 4). The mean temperature in the mixing chamber was found to be of the order of $1000^{o}C$. It increased to a higher value at the entrance to the combustion chamber after which it dropped in the axial direction throughout the combustor and tail pipe (Fig. 5). All temperatures increased as the fuel air ratio approached unity. The combustion efficiency was determined to be nearly 100% for all combustors except near the rich limit where it dropped by 3-4% (Fig. 6). Correspondingly, CO levels were found to be of the order of 20 ppm except near the rich limit (Fig. 7). The NO_x levels were approximately 30 ppm at the lean limits, rose to about 60 ppm at stoichiometric before falling slightly near the rich limit (Fig. 8).

All the above described parameters were not noticeably affected by changes in the combustion chamber diameter or length as long as the chamber volume was kept constant. An increase in the combustion chamber volume, however, did result in a lower pulsating frequency (Fig. 3) and a lower dB level (Fig. 4). It is this reduction in dB level which caused a reduction in the fuel and air flow rates for given valve settings and fuel air ratios (Fig. 2). Mean temperatures throughout the burner were also higher the smaller the combustor volume (Fig. 5). The combustion efficiencies were close to 100% for all combustors but dropped most significantly near the rich limit for the smallest combustor (Fig. 6).

Acoustic pressures at various locations in the different combustors and at a number of fuel air ratios are presently being measured. The acoustic frequencies are very regular but fluctuations in amplitudes have been observed (Fig. 9). Special attention is being paid to the behavior of the pressure signal during combustor start-up and shut-down in order to determine the driving and damping characteristics of the pulse combustor.

Comparison of the shadowgraphy, Schlieren and C-C or C-H radiation results obtained largely in the previous year indicated that there is a pronounced increase in the radical concentration and, thus, probably the reaction rate when the fuel and air jets first impinge on each other. Cycle to cycle reignition of the new reactants coincide with the instant when new fuel and air first mix. Similar observations were made using the low sensitivity. Schlieren set-up as described in last years annual report. The ignition source for the new reactants may be expected to consist of entrained radicals left over in the mixing chamber from the previous cycle. In this connection it should be pointed out that it is well known that under certain conditions the entrainment rates of pulsating jets are considerably higher than those of steady jets.

Flow visualization using particle tracking were carried out using still and high speed cine-photography. Particle tracks were clearly visible showing the air entering the mixing chamber and the ensuing turbulent mixing. The overall flow patterns thus observed were similar to the ones seen in the shadow visualizations. However, the particle tracks were not as clear as the shadowgraph/Schlieren markings, since a significant part of the energy in the laser light sheet is reflected as it passes through the curved surfaces. The particles are also quickly swept out of the vertical laser light sheet in the axial, downstream direction.

Additional high speed shadowgraph movies are currently being obtained in order to investigate the fuel and air flow patterns and their mixing near the limits of flammability of the combustor. First observations obtained under conditions for which pulse combustion can only be maintained for some 10-20 secs after the spark plug is switched off indicate significant differences in the timing of the individual steps in the pulse combustion process such as fuel and air injection, mixing, the appearance of large regions of uniform combustion products etc. In particular, it was noted that while under regular conditions fuel and air jets enter at the beginning of each cycle into a mixer head filled with combustion products at uniform temperature with only a few reacting pockets in evidence, near the operational limit the fuel and air jets appear while the mixing chamber is still filled with what appears to be reacting pockets at different temperatures. This phenomenon will be further investigated during the coming year.

Due to personal difficulties encountered by the graduate student working on the analytical model, progress in this area was slow. Efforts concentrated on the derivation of the required wave equations, the modelling of the flapper valves and combustion process dynamics and the choice of an appropriate solution technique.

WORK PLANNED FOR THE COMING YEAR

During the next contract year the acoustic pressure measurements will be completed in all combustors over the full range of fuel air ratios. Special attention will be paid to the transient behavior of these pressures during start-up and shut-down which will permit the determination (or estimation) of the driving and damping characteristics of the combustor. For this purpose a single spark ignition system activated after a variable time delay by the fuel selonoid valve is being constructed to avoid interference by the continuous spark presently used with the pressure transient recordings during start-up.

Additional high speed Schlieren and shadowgram movies and C-C and C-H radiation measurements will be obtained to determine the mixing patterns at each phase in the cycle and a the phase relationship between mixing and ignition for the combustors operating near their operational limits. These findings will be compared with those obtained while the combustor is operating under optimal conditions.

An additional, essentially cylindrical combustor fitted with flat windows along the curved walls will be constructed. This new unit will permit not only Schlieren and shadowgraphy from a side-on view but also facilitate better LDV measurements. LDV measurements will be carried out in order to map the complex flow field in the mixing and combustion chambers and in the tail pipe. This will not only permit a quantitative description of the flow field but also a determination of the extent of back flow in the various parts of the combustor and of the residence time of the charges in the pulse combustors. Finally, the modelling efforts on the pulse combustors will continue.

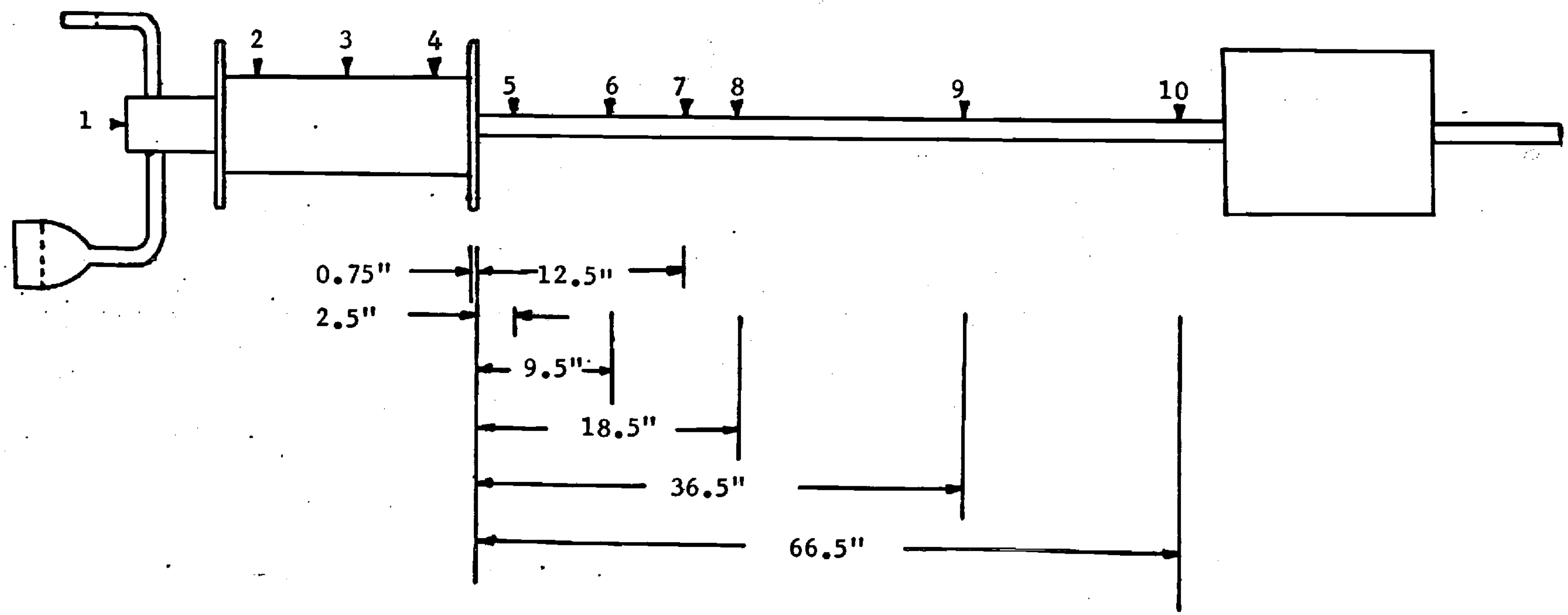


Figure 1. Location of Pressure and Temperature Measurement Positions in the Pulse Combustors.

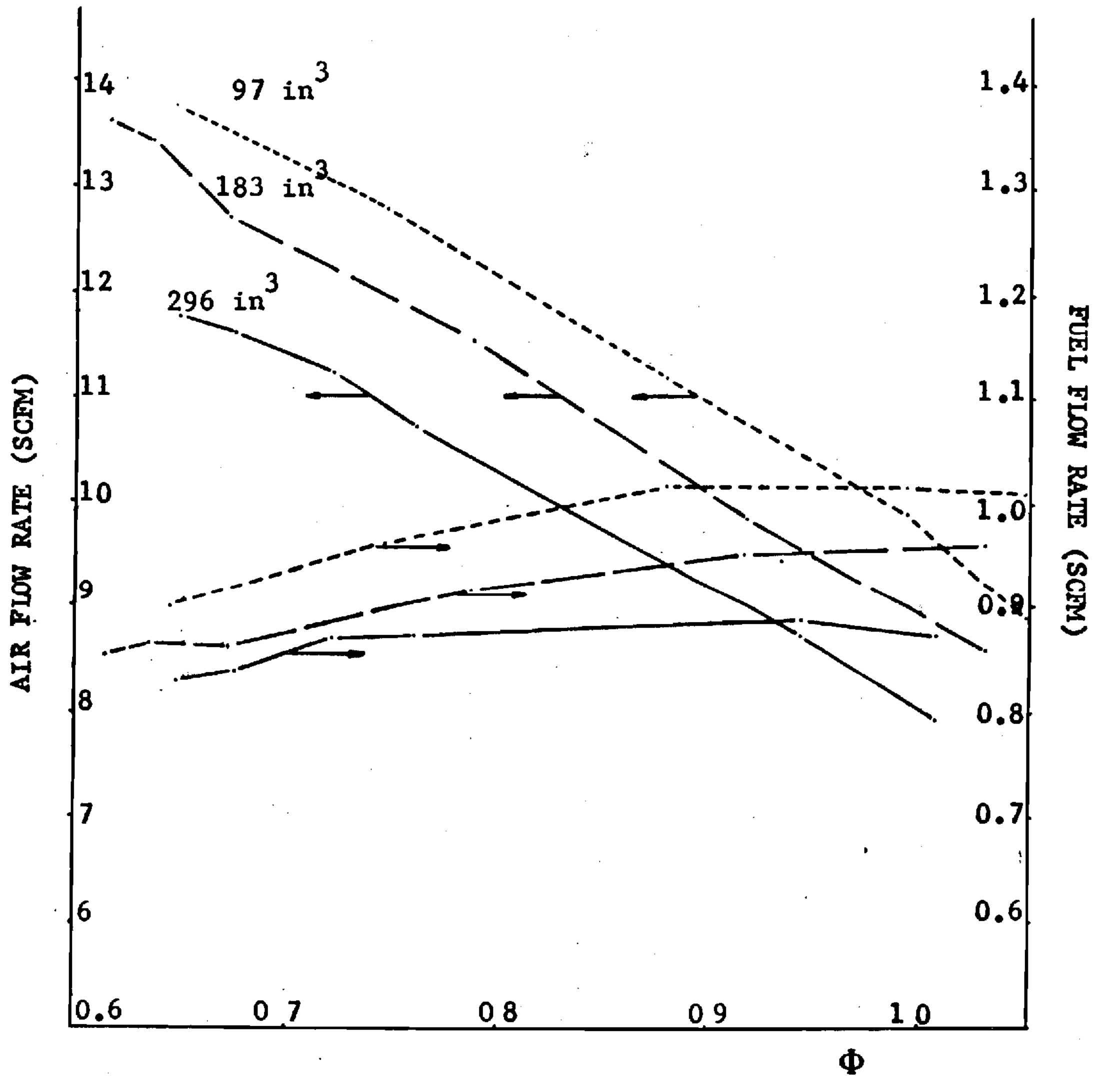


Figure 2. Fuel and Air Flow Rates vs. Fuel-Air Ratio for Combustors of Three Different Volumes.

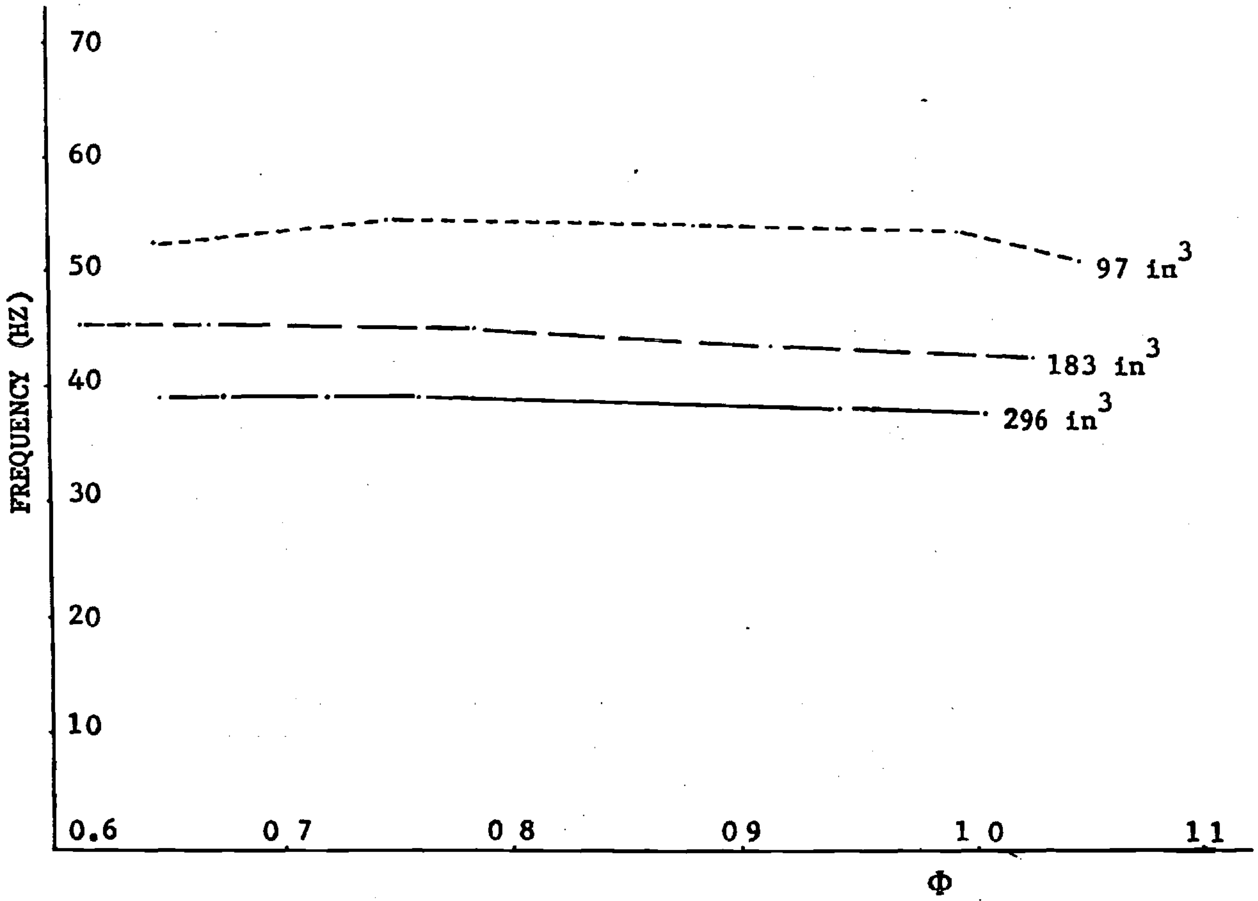


Figure 3. Frequency vs. Fuel-Air Ratio for Combustors of Three Different Volumes.

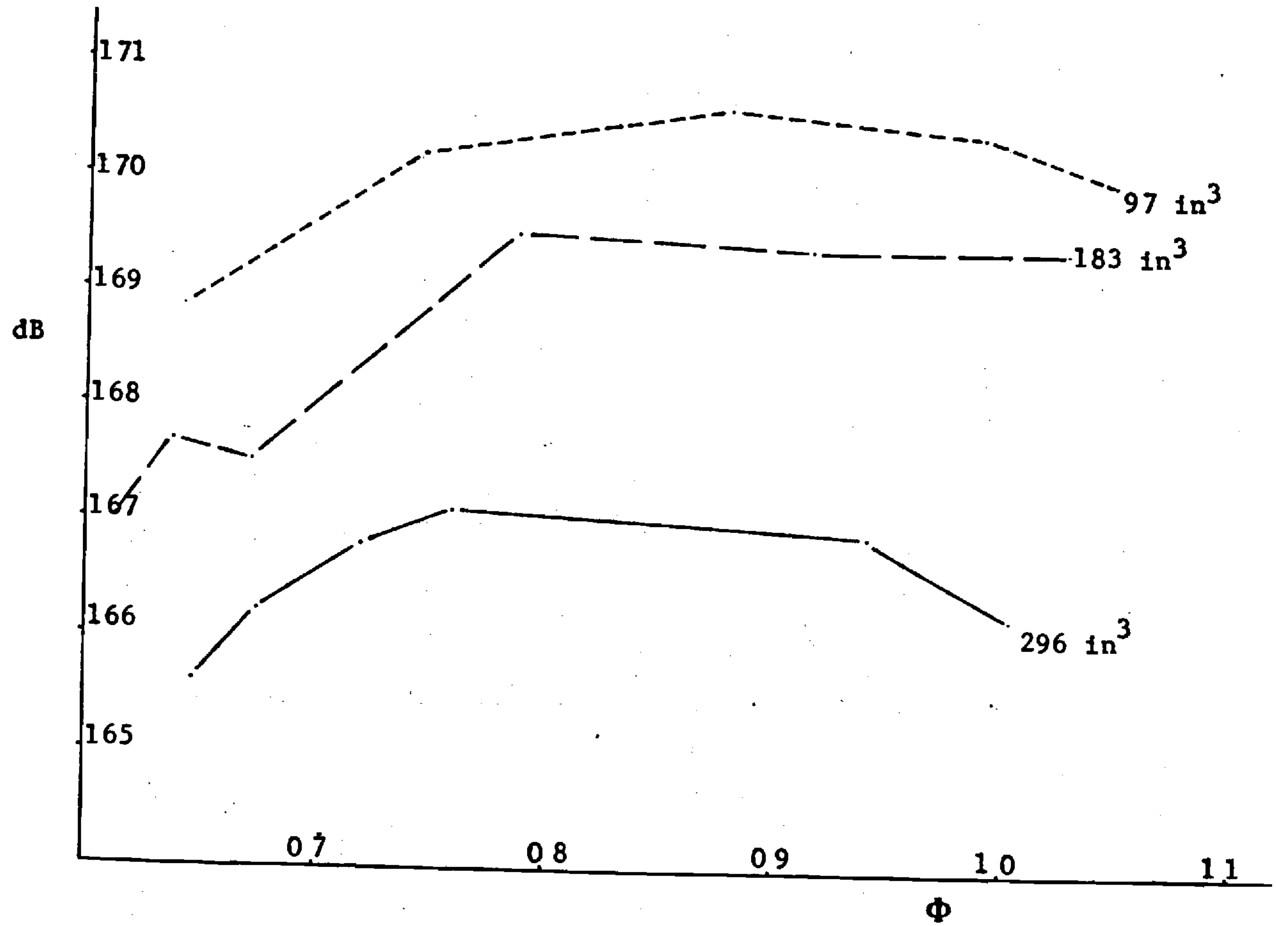


Figure 4. DB. level vs. Fuel-Air Ratio for Combustors of Three Different Volumes.

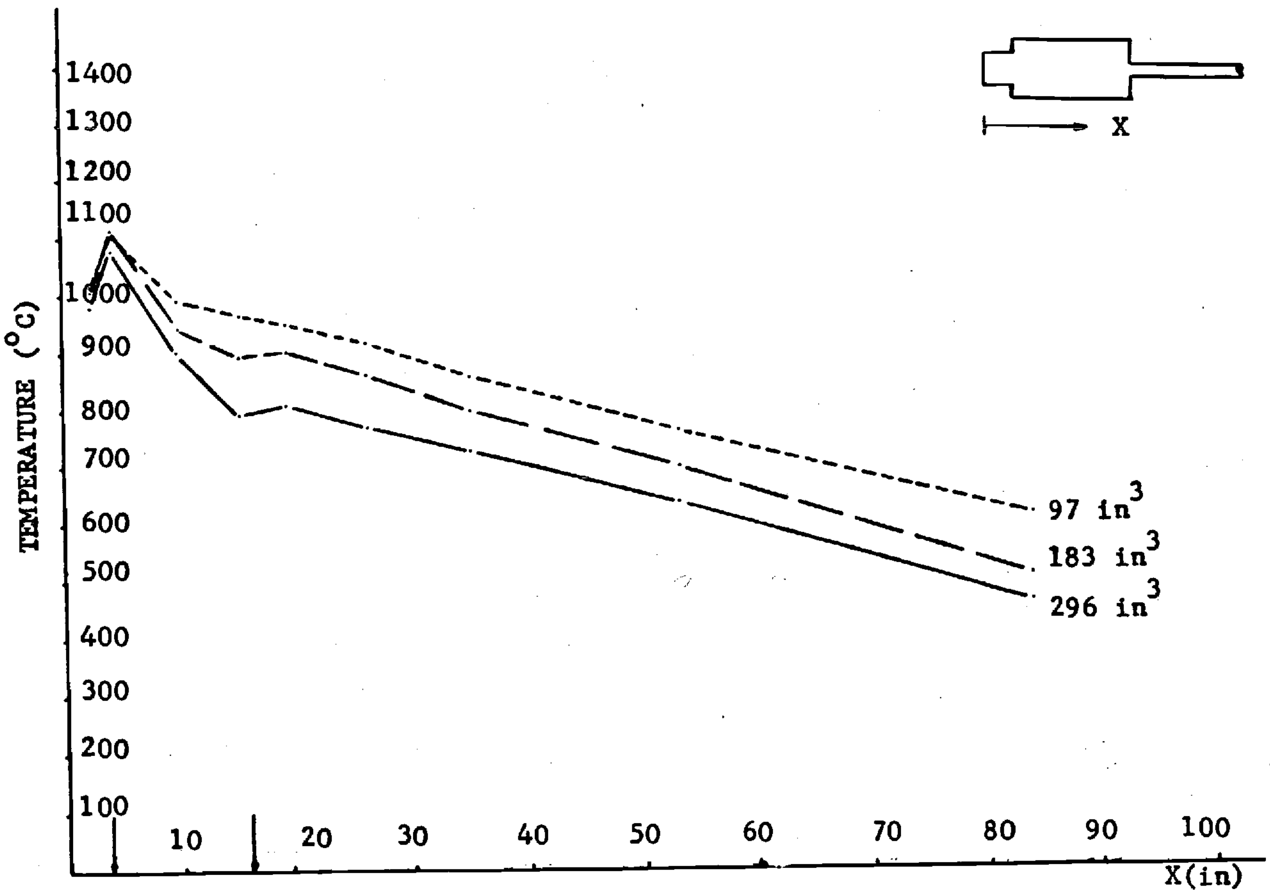


Figure 5. Mean Axial Temperatures vs. Axial Distance for Three Combustors of Three Different Volumes.

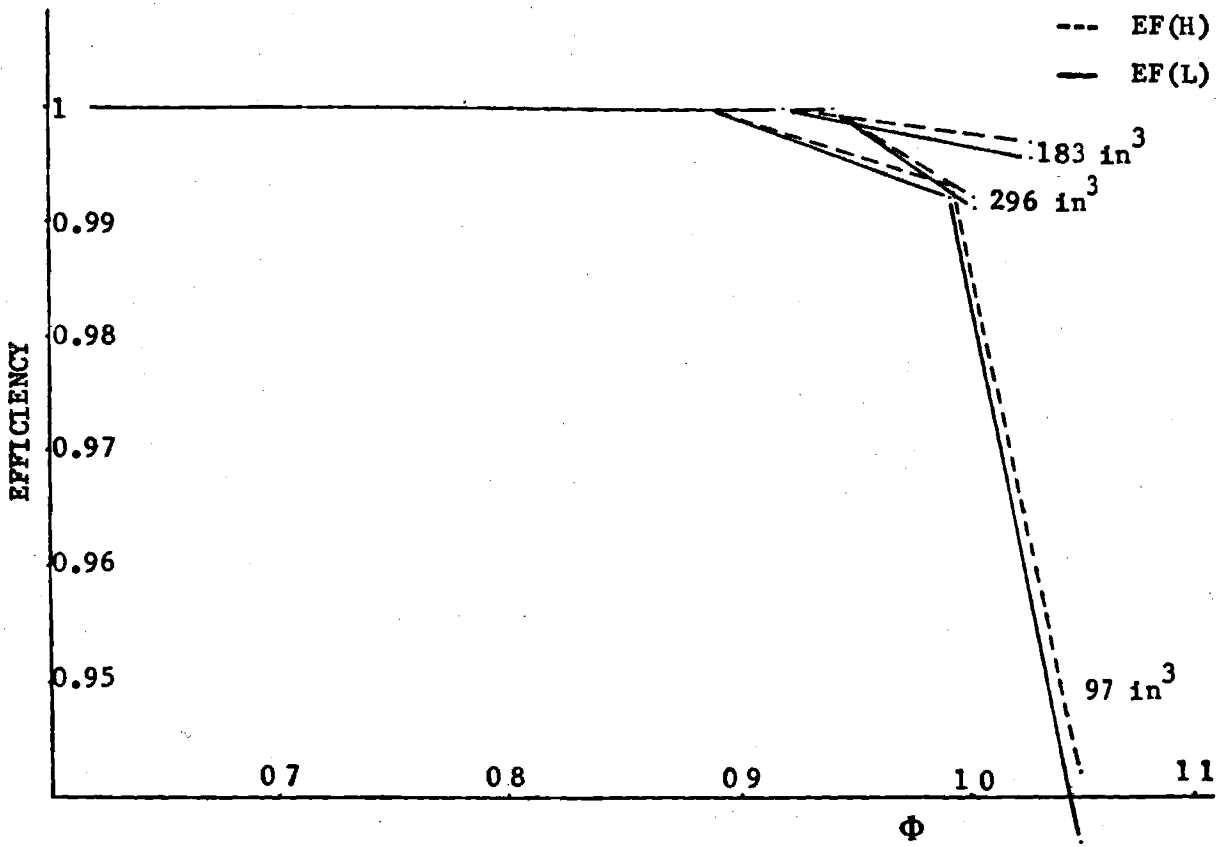


Figure 6. Efficiencies using High Heating Value (H) and Low Heating Value (L) of Methane vs. Fuel-Air Ratio for Combustors of Three Different Volumes.

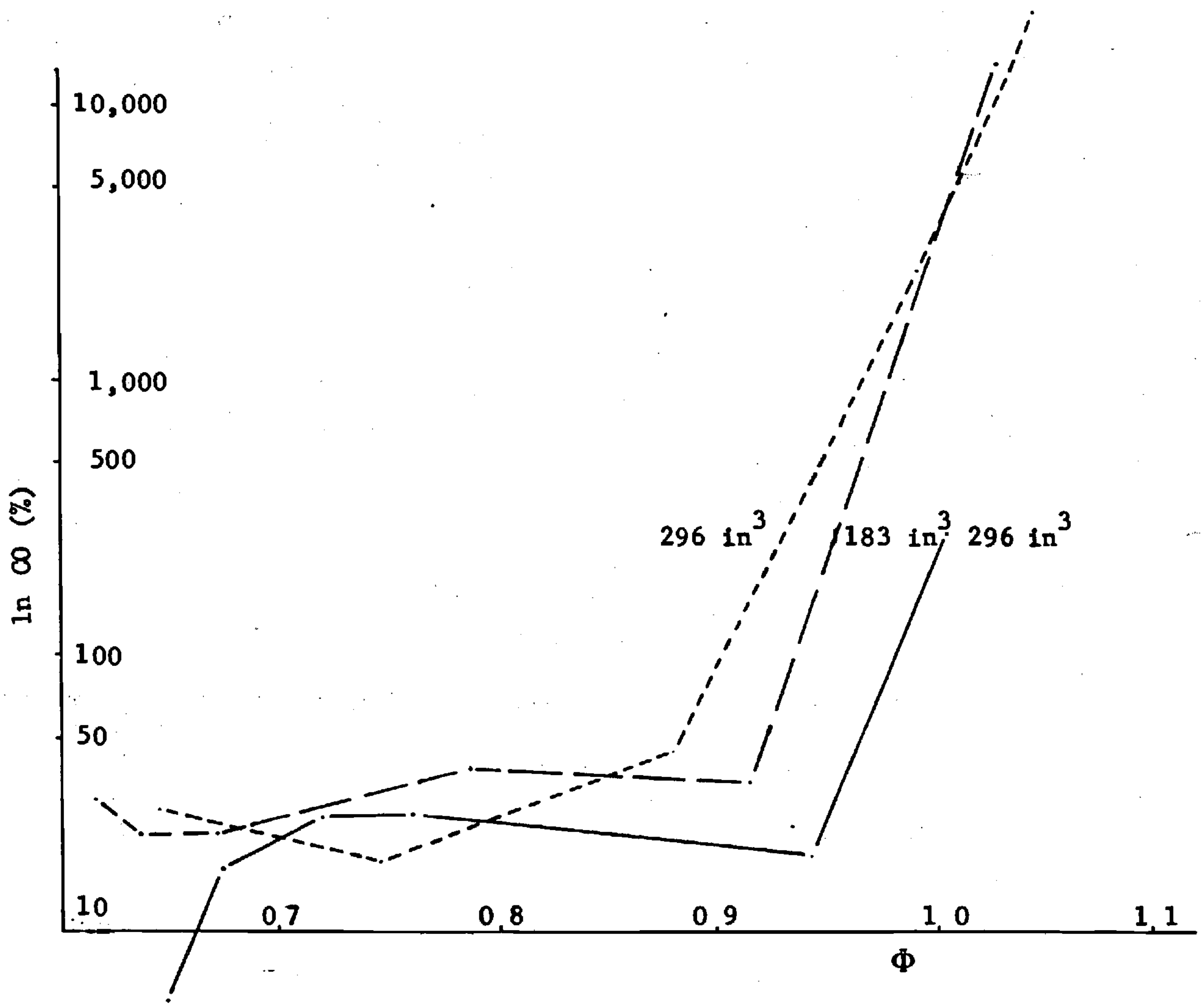


Figure 7. CO_2 Concentrations vs. Fuel-Air Ratio for Combustors of 3 Different Volumes.

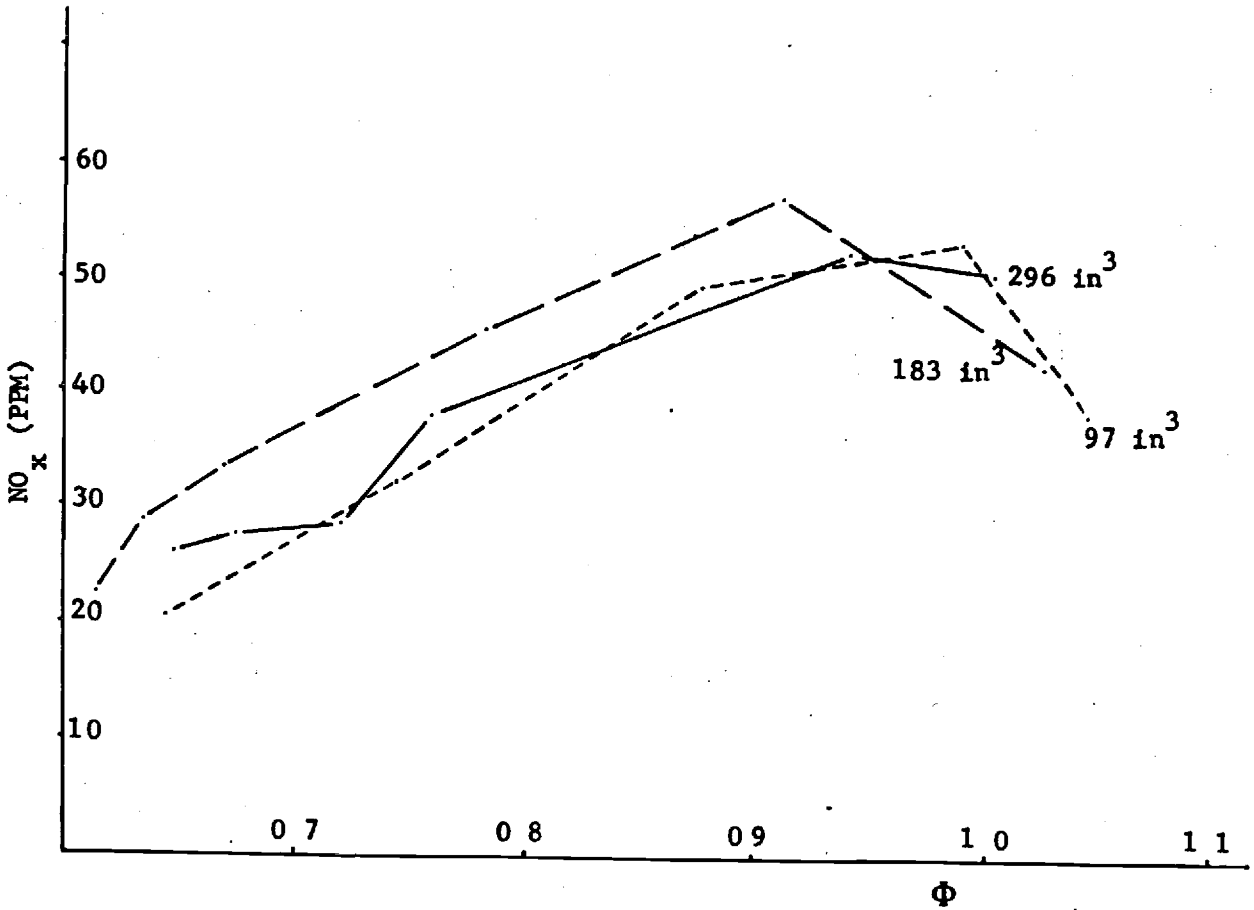


Figure 8. NO_x Concentrations vs. Fuel-Air Ratio for Combustors of Three Different Volumes.

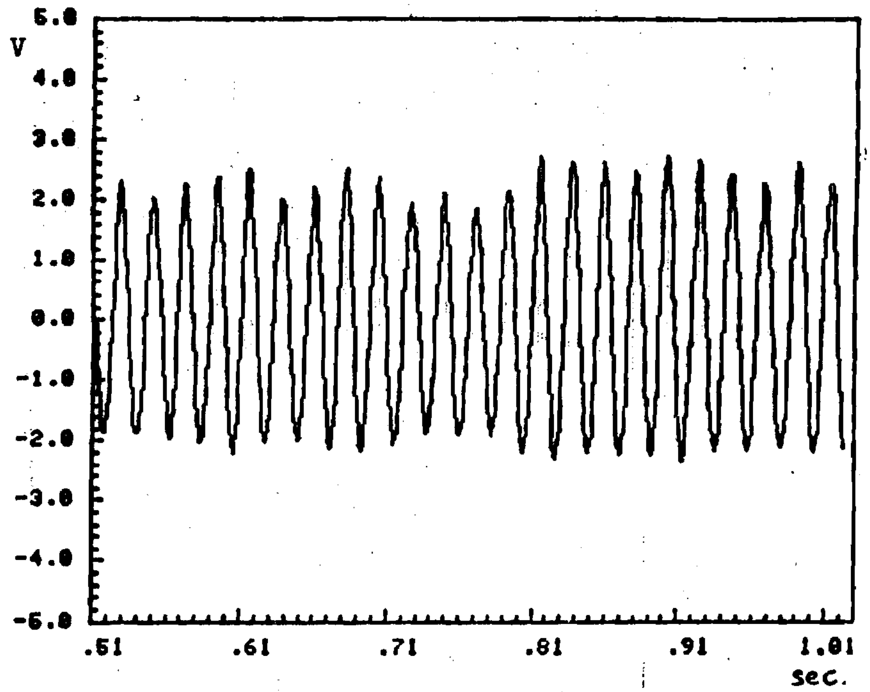


Figure 9. Representative Sample of Acoustic Pressure Oscillations in Pulse Combustor.

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. GRI 185-0032	2.	3. Recipient's Accession No. GRI/85-0032

4. Title and Subtitle Pulsating Burners - Controlling Mechanism and Performance	5. Report Date March '85 (approved)
	6.
7. Author(s) B. T. Zinn, B. R. Daniel and J. I. Jagoda	8. Performing Organization Rept. No.
9. Performing Organization Name and Address School of Aerospace Engineering Georgia Institute of Technology Atlanta, GA 30332	10. Project/Task/Work Unit No. E-16-662
	11. Contract(C) or Grant(G) No. (C) 5083-260-0873 (G)
12. Sponsoring Organization Name and Address Gas Research Institute 8600 West Bryn Mawr Ave. Chicago, IL 60631	13. Type of Report & Period Covered Annual Dec 1, 83 - Nov 30, 84
	14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

Although gas fired pulsed combustors for home heating have now been on the market for a number of years, little is known about the physical and chemical processes which control the operation of these devices It is the objective of this study to gain an understanding of these processes such as mixing cycle to cycle reignition and flame propagation in the burner. Such an understanding would permit a more rational approach towards the design of future combustors. Early tests have shown that the frequency of pulsations are a function of combustor volume and the combustor thus behaves as a Helmholtz resonator. Visual observations, high speed shadow and Schlieren photography, and C H and C-C measurements were carried out in partially transparent combustor. Combustion was seen to occur largely in the mixing chamber Fuel and air jets were seen to enter the mixing chamber collide and mix. The new reactants are ignited by entrained radicals remaining from the previous cycle. Ignition takes place at the location and the time at which the two reactant streams first mix. The combustion then spreads with the flow throughout the mixing chamber in two opposing vortices. The reaction process never ceases at any time in the cycle.

17. Document Analysis a. Descriptors

Pulse Combustor

b. Identifiers/Open-Ended Terms Mixing, Reignition, Visualization, Radiation Measurements, Performance

c. COSATI Field/Group Combustion

18. Availability Statement	19. Security Class (This Report) Unclassified	21. No. of Pages
	20. Security Class (This Page) Unclassified	22. Price

(See ANSI-Z39.18) See Instructions on Reverse OPTIONAL FORM 272 (4-77) (Formerly NTIS-35) Department of Commerce

Pulsating Burners - Controlling Mechanisms and Performance

Annual Report

December 1, 1983 - November 30, 1984

Prepared by

B. T. Zinn, B. R. Daniel and J. I. Jagoda

School of Aerospace Engineering

Georgia Institute of Technology

For

Gas Research Institute

Grant No. 5083-260-0873

GRI/85-0032

GRI Project Manager

James A. Kezerle

Combustion

December 10, 1984

RESEARCH SUMMARY

Title	Pulsating Burners - Controlling Mechanisms and Performance
Contractor	Georgia Tech Research Institute
Contract Number	GRI Grant 5083-260-0873
Principal Investigators	B. T. Zinn, B. R. Daniel and J. I. Jagoda
Objective	The objective of this study is to gain an understanding of the fundamental processes, such as mixing and cycle to cycle reignition, which control the operation of gas fired pulsed combustors. An analytical model is to be developed which will provide a rational procedure for the design and scaling of these burners.
Technical Perspective	In spite of the fact that gas fired pulsed combustors for home heating have now been on the market for a number of years, little is known about the physical and chemical processes which control the operation of these devices. Of particular interest are the mixing of fuel and air, cycle to cycle ignition and the nature of the flame propagation in the burner. Such information is necessary for improving the operational characteristics of existing pulsating combustors and for guidance in the development of new burners for increased capacity or novel applications. Furthermore, the acquired insight will be used to guide the development of a theoretical model for predicting the behavior of pulsating combustors. The availability of such a model would permit the replacement of the costly empirical trial and error methods used to date for the design and scaling of pulsed combustors by a more rational approach.

Technical Approach

As a first step, a parametric study is being carried out using steel combustors in order to determine the influence of the combustor geometry on its performance and efficiency. Selected burners have and will be fabricated in pyrex and quartz and their flow field investigated using high speed cinematography Schlieren/shadowgraphy, stream line and mixing visualizations as well as laser Doppler velocimetry (LDV). Lastly, C-H and C-C spectroscopy is being used in the determination of the timing, location and rate of heat release during the combustion cycle. A linear and, if necessary, a non-linear theoretical model of the combustor is being developed to provide a basis for future pulsating combustor design and scaling.

Results

During the past year, a test matrix for the parametric study of the performance of gas fired pulsating combustors (GFPC) has been developed. All components required to assemble the 10 combustors in the test matrix were fabricated. Pyrex end plates for the mixing and combustion chambers which can be used for all 10 combustors have also been obtained and the hardware required to fit them to the combustors has been fabricated. An all pyrex combustor for optical diagnostics has been developed and tested. Early problems with explosions in the glass combustor during ignition have been solved. An exhaust gas analysis train to determine the combustion products composition and, thus, the combustion efficiencies has been designed and constructed. A scheme for determining combustion efficiencies from the analysis of the exhaust gases has been developed. The software for acquiring and analyzing the temperatures, pressures, exhaust gas compositions and combustion efficiencies of the combustor has been written for an HP series computer. A two component LDV system and the computer for its data acquisition have been set up and are currently being tested. An optical set-up for measuring C-C and C-H radiation and a high speed Schlieren and shadowgraph system have been placed in operation. Two systems for particle tracking and mixing visualizations have been set up and successfully tested.

Initial performance tests have been carried out on all ten combustors in the test matrix. All ten combustors operated satisfactorily although the large volume combustors were somewhat more difficult to ignite. Analysis of the data, using a simplified model, showed that for the tested combustors the combustor volume is the parameter which controls the frequency of pulsations. This analysis also showed that the developed combustors operate as Helmholtz resonators.

Visual observation in the all pyrex combustor showed that for this configuration most of the combustion actually takes place in the "mixing " chamber. High speed Schlieren and shadowgrams were used to visualize the incoming fuel and air jets, their mixing and combustion. Low sensitivity Schlieren was used to separate the Schlieren markings due to hot and cold gas interfaces from those due to flame fronts. C-H and C-C radiation from the entire combustor were measured for relatively lean, relatively rich and optimum combustion conditions. The latter corresponded to those used in the visualization studies. These measurements strongly suggest that the reaction does not cease at any time during a cycle of operation. Furthermore it was observed that the magnitudes of the radiation fluctuations decreased as the air flow is reduced (i.e., the fuel air ratio increases). At the same time, the pressure amplitudes remained essentially unchanged. Finally, comparison of the shadowgram and radiation results indicated that both C-C and C-H radiation sharply increased at the instant in each cycle at which the new fuel and air jets first mix. This suggests that the ignition of the new reactant occurs at that instant.

Project Implications

In the first year of this research effort, investigators at Georgia Tech have identified and utilized many diagnostic tools effective in the study of pulse combustors, demonstrated and modeled the dependence of pulsation frequency on combustor volume, and identified significant characteristics of the many processes that are inherent to stably operating pulse combustors. The challenge now is to fully utilize those diagnostic techniques to probe the relationships between the various cycle-to-cycle processes and determine which control combustor operation. This knowledge will guide further modeling efforts. Although productive working relationships have been established between researchers at Georgia Tech, Battelle, AGA Laboratories, and Sandia National Laboratory, it appears that the greatest progress in the coming year can be made by involving researchers with superior knowledge on the individual but interdependent processes investigated in pulse combustors. Discussions with other GRI contractors, such as Paul Dimotakis (mixing), Dave Crosley (ignition), and Charlie Westbrook (chemical kinetics), will be encouraged at the 1985 GRI Combustion Contracts Review Meeting and Pulse Combustion Workshop (March 25, 26 and 27 in Atlanta). GRI, Battelle, and Georgia Tech have agreed that focusing on controlling processes in pulse combustors is the proper way to proceed and detailed work plans have been established on that basis. Adherence to these plans will be essential to further important progress on this contract.

INTRODUCTION

The objective of this study is to gain insight into the fundamental processes responsible for the operation of gas fired pulsed combustors and to develop an analytical model capable of predicting the performance characteristics of new pulsed combustor designs. Furthermore, the model will consider the effect of scaling upon combustor performance. To this end, the effects of a number of geometrical combustor parameters, such as L/D ratio, combustor volume and exhaust pipe length and diameter, upon the combustor performance are under investigation. Also, the interactions between the pulsed flow field and combustion processes are being studied. Special emphasis is placed on determining the source and location of the cyclic ignition and following the flame spread in the combustor. The streamlines in the flow field and the mixing of fuel and air are being visualized and recorded. Velocities and species concentrations are measured using LDV and Raman. An analytical model is being developed which will predict the performance of combustors having different geometries and scales. The insights gained from the above experiments will be used in the development of the model which will, in turn, be tested against further experimental data. It is, thus, anticipated that this study will enable the industry to abandon the currently used empirical approach in the design and development of pulsed combustors in favor of a rational design procedure based upon dependable model predictions.

Program Plan

The program is divided into three major tasks as outlined below:

Task I - Experimental Investigation

A. Performance Evaluation. The performance of a number of combustors of different geometries (i.e., different L/D, volumes, tail pipe lengths, etc.) is being investigated using temperature, pressure and combustion efficiency measurements. For each configuration, the performance is evaluated over a range of air/fuel ratios and fuel loadings.

B. High Speed Cinematography. This technique is used to determine the locations of cycle to cycle ignition and the shape and motion of the flame.

C. Flow Visualization. Stream lines are being investigated by recording the tracks of seed particles moving through a laser light sheet. This process is repeated with the laser sheet at different combustor locations. Refractive index gradients caused by the flame front or by pockets of hot and cold gases are visualized using Schlieren and shadowgraphy.

D. Mixing Visualization. Mixing patterns are being recorded photographically by heavily seeding either the fuel or the air and illuminating the transparent combustor using a laser light sheet. Again, the visualization is repeated with the laser sheet at different combustor locations.

E. LDV. Although the bulk of the laser Doppler velocimetry measurements will be carried out in the second and third years, the system has been set up during the first year. The data acquisition system previously developed is being modified to permit ensemble averaging over a number of cycles and the problem of beam displacement due to the cylindrical walls is being addressed.

F. C-H & C-C Spectroscopy. Although this part of the study was originally reserved for the second and third years,some measurements were already carried out and significant results obtained. Radiation from the combustor is passed through the respective filters and its intensity measured using a photomultiplier. The radiation measurements are then related to combustion intensities.

Task II - Analytical Study

A theoretical model which describes the performance of the investigated combustors is being developed. The model will incorporate the findings of the experimental phases of the program. The model will be linear and investigate the possible range of operating conditions of the burners. Should this not result in satisfactory agreement with the experimental data, the non-linearities of the problem will be incorporated in the model.

Task III - Reporting

As per contract agreement.

TECHNICAL PROGRESS AND RESULTS

During the past year, ten combustors of different dimensions as shown in Figs. 1 and 2 were fabricated and tested. In a typical test, the pressure oscillations were measured in the mixing chamber, at three axial positions in the combustion chamber and at two positions in the exhaust pipe, see Fig. 2. The measured pressure oscillations were displayed on an oscilloscope and their frequencies and dB levels were measured digitally. Furthermore, mean temperatures were determined using shielded Pt-Pt 13% Rh thermocouples at the same locations as the pressure measurements. Lastly, temperature traverses were carried out in the standard AGA combustor (i.e., combustor No. 1).

All combustors performed satisfactorily although the large volume burners were more difficult to start, (i.e., combustors 5 and 9). Explosions encountered in these combustors have been eliminated by modifying the ignition procedure. The reasons for the ignition difficulties with the larger combustors need, however, to be further investigated.

Typical pressure traces measured in the combustor and the tail pipe are shown in Fig. 3. These pressure signals show reasonable cycle to cycle reproducibility. Furthermore, the measured pressures are not purely sinusoidal as the combustor pressure shows the presence of a higher harmonic and the tail pipe signal has a high frequency oscillation superimposed upon the fundamental oscillation. Examination of the spatial dependence of the pressure signals showed a drop in pressure amplitude between the combustor and the tail pipe which was probably caused by acoustic losses associated with the transition between the large diameter combustor and the smaller diameter tail pipe.

The measured pulsations frequencies were correlated with different characteristic combustor dimensions and combinations thereof in an effort to determine the parameters which controlled the pulsation frequency. Since the tail pipe length and diameter remained fixed in all of the tests, its influence was not considered in this study. This analysis showed that for the combustors investigated to date, the frequency of pulsations depended primarily upon the combustor volume, see Fig. 4.

A correlation of the measured data (Fig. 4) with the results of initial analytical studies showed that the investigated pulsed combustors behave like Helmholtz resonators, whereby a long tail pipe replaces the short neck of classical Helmholtz resonators. The main results of the initial model are presented in Figs. 5 and 6. The initial model assumed that the amplitudes of the oscillations were small (i.e., linear model) and that conditions inside the combustor were uniform at each instant of time. The expressions presented in Fig. 5 present a scheme which will enable one to determine the combustion driving R_r (i.e., the real part of R which is defined in Fig. 5) from the measurements of the amplification and decay rates of the oscillations. The expressions presented in Fig. 6 show that for fixed values of combustor length, tail pipe area and c the frequency of the burner is only a function of the combustion volume V, as has been demonstrated by the results presented in Fig. 4.

Analysis of the temperature data (see Fig. 7) showed that the measured mean temperatures reached their maxima in the mixing chamber and decreased thereafter. This observation strongly suggests that combustion most likely starts in the mixing chamber. The observed rapid temperature drop is undoubtedly caused by the high heat losses to the combustor walls which are known to occur when pulsations are present in the flow. Temperature traverses in the AGA combustor showed much higher temperatures near the combustor center than at its wall. This is particularly pronounced near the mixing chamber.

Transparent pyrex end plates were fabricated for the mixing and combustion chambers. End-on Schlieren and shadowgraphy have been carried out using the partially transparent combustor. These transparent end plates can be installed on all ten combustors used in the above mentioned parametric study. An all pyrex combustor has been constructed and tested. The combustor performed well initially although the first version was eventually destroyed by an explosion. The valve which caused this explosion has since been replaced and no further problems have been experienced. The quality of the blown pyrex is, however, insufficient for Schlieren measurements but should be acceptable for streamline and mixing visualizations and for LDV measurements.

Visual observations showed that for this configuration most of the combustion actually takes place in the part of the burner generally referred to as the mixing chamber, with only a central flame cone extending into the combustion chamber. Pressure traces are recorded simultaneously with the Schlieren and shadowgraph images in order to permit a coordination between the visualization image and the phase in the cycle. High speed (7000 fps) Schlieren and shadowgraphy motion pictures clearly showed a highly turbulent jet of fuel gas entering the mixing chamber. Shortly afterwards a wider air jet enters the chamber at right angle to the fuel and collides with the side of the fuel jet just as that reaches the opposite wall. The interaction between the two jets sets up two vortices in opposite directions, as observed by the interfaces of hot and cold gas pockets visualized by these refractive techniques (Fig. 6). (Refractive index changes between pockets of gases of different composition but equal temperature are relatively small and may be expected not to affect the shadowgram markings significantly.) As combustion proceeds an increased number of smaller turbulent pockets of hot and cold gas appear. Towards the end of the cycle, as combustion nears completion, an area of uniform refractive index appears in the upper part of the chamber. This uniform temperature area spreads with time until it covers most of the observed area. Some pockets of reactants are observed, however, in parts of the mixing chamber until a new fuel jet appears and a new cycle commences.

Since the shadowgrams and high sensitivity Schlieren are incapable of differentiating between interfaces of hot and cold gases and actual flames, the Schlieren system was made less sensitive to assure that only the large temperature gradients associated with flame fronts are observed. Records obtained under these conditions suggest that in a given cycle combustion is initiated at the location where the air jet impinges on the fuel before spreading throughout the chamber.

C-C and C-H radiation intensities have long been considered a measure of combustion intensity, see Ref. 1. However, insufficient information on the kinetics of the combustion of methane is currently available to state with certainty that excited C-C and C-H radicals are true intermediates of the combustion of methane in a true, selfsustaining, exothermic, flame as traditionally defined. Nevertheless, because of the short life time of these excited radicals (nanoseconds) the detection of C-C and C-H indicates the presence of a chemical reaction in the combustor. These radiation intensities were, therefore, measured using suitable filters placed in front of a photomultiplier which collects light from the entire mixing chamber (Fig. 9). The radiation fluctuations were found to be almost inphase (although and slightly leading) with the pressure oscillations. C-C and C-H radiation traces are shown in Figs. 10 and 11 respectively for three operating conditions of the combustor. Pressure traces are also shown for reference. The three conditions reported are near the lean and rich operating limits of the combustor and for the mid range. The latter corresponds to the condition at which the Schlieren and shadowgram visualizations were carried out. In all cases the radiation slightly leads the pressure. The C-C radiation shows a sharp peakearly in the cycle for all but the rich limit case. This is far less pronounced in the C-H radiation. These findings agree well with observations made in laminar diffusion flames where C-C radiation was observed to be emitted prior to C-H radiation. For both the C-C and C-H radiation the fluctuations decrease with increasing fuel richness in the combustor. In contrast, the pressure amplitudes do not decrease as the operating conditions change. Further work is needed to definitvely establish the reasons for the observed behavior near the rich limit.

Of importance is the observation that at no instant during the cycle does the radiation disappear. While not enough is presently known about the kinetics of methane combustion to state definitively that this means that the "flame" never goes out during the cycle, it can be concluded that excited radicals are present in the combustor at all times. It is possible that these radicals act as a pilot for the new charge. In fact, during extinction it was noted that the radiation minimum decreases during consecutive cycles until it reaches zero from which it never recovers (Fig. 12).

Comparing the phase of those radiation measurements with the shadowgraph and Schlieren visualization indicated that the period during which a rapid increase in the radiation levels is recorded coincides with the time in the cycle when the air jet first impinges on the fuel, signalling the beginning of the combustion cycle. This observation along with the low sensitivity Schlieren visualizations, which show that the first appearance of a flame front occurs in the region where fuel and air dust mix, indicates that the new combustion cycle commences at the location where and the instant when the fuel and air jets first impinge upon one another. The precise nature of the ignition source remains to be determined. However, radicals observed to have been remaining in the mixing chamber from the previous cycle may have been entrained by the fuel and air jets and may act as ignition sources. Since ignition of the new charge seems to occur immediately after the fuel and air jets collide it appears that the ignition process is controlled by jet entrainment and mixing rather than by diffusion and backflow from the main combustor.

The optics for generating a light sheet for mixing and streamline visualization have been set up Two systems are now available (Fig. 11). One uses the beam from the 5 watt Ar-ion laser also used for the LDV which is expanded using a cylindrical lens. In the second version the same laser beam is expanded slightly in one dimension and then undergoes multiple reflections between two slightly inclined flat mirrors resulting in a light sheet. The multiple use of the beam in the second version provides better illumination intensity throughout the sheet, but is less suitable for curved glass surfaces since once the beam is deflected by the curved surface the remainder of the sheet is lost. Both systems are now operational as is a seeding system. Both flows will be lightly seeded for streamline recording while one flow only will be heavily seeded for mixing visualization. Both still and high speed cine records are planned for recording to the streamline and mixing patterns.

A two component LDV has been set up along with an HP A700 computer data acquisition and reduction system. This equipment is currently being tested. The data reduction program is also being modified to permit ensemble averaging of the data which is necessary to correlate the velocity data with their appropriate phase during the cycle. Corrections are also being prepared for the deflection of the LDV beams as they pass through the curved pyrex surfaces of the combustor.

Finally, a chemical sampling train has been set up which permits the analysis of the exhaust gases and, thus, will be used to determine the combustion efficiency of the pulsed combustors. The species whose concentrations can be measured include CO, CO_2,

NO_x, unburnt hydrocarbons and soot. A computer program has been written which permits on line acquisition of pressures, temperatures and gas analysis data. The program is capable of analyzing and quantifying the fluctuating data and to calculate combustion efficiencies from the measured exhaust gas compositions. Preliminary checks of this computer program are currently being carried out.

The above findings permit a response to some of the questions raised in J. Kezerle's recent GRI memo on pulse combustion dated October 1, 1984, although some of these answers require further confirmation. The question will be addressed in the order in which they appear in Attachment No. 2 in that memo and will be numbered in that sequence.

A1: Radiation measurements have shown that chemical reaction does not cease between cycles.

A2: Reignition of the new charge seems to occur near the center of the mixing chamber where the air first impinges on the fuel jet.

A4: Reignition seems to occur as soon as the air flow impinges on the fuel jet just prior to the minimum in pressure.

A5: So far it has not been possible to identify a single flame front. The combustion zone appears as a turbulent moving group of small pockets of hot and cold gas.

B2: The fresh fuel jet actually reaches the opposite wall before the new air charge impinges on the fuel jet at which point reignition seems to occur.

D2: See A4.

Confirmation of these replies and the answer to all other questions posed in this memo must await further experimentation.

WORK PLANNED FOR THE COMING YEAR

During the next contract year efficiency, performance and NO_x emission measurements will be carried out on the ten combustors which have so far been tested. One more combustor will be fabricated in which the combustion chamber diameter is equal to that of the mixing chamber which effectively eliminates the step between the mixing chamber and the combustion chamber. This will help determine the effect, if any, of this step on the flame stabilization or the ignition of the new charges.

In addition one further combustor will be designed and constructed which, while essentially cylindrical in shape, will be fitted with flat windows along the curved walls. This will permit high speed Schlieren and shadowgraphy to be carried out from a side-on view as well as from and end-on view as has been done during the past year. This, in turn, will increase the understanding of the complex, 3-D flow in the pulsed combustor. In addition the flat windows will be beneficial for the LDV measurements.

The optics and seed injection systems for the streamline and mixing visualizations will be improved. To maximize the use of the energy in the laser beam a system will be designed which will sweep the unexpanded beam rapidly through the test region. In addition, the design of an injection system will be attempted which will permit particle injection during one cycle only for better mixing visualizations. LDV measurements will be carried out in order to map the complex flow field in the mixing and combustion chambers and in order to address some of the issues outlined in the memo to GRI dated Feb. 13, 1985. These include the importance, if any, of backflow, the acoustic boundary layer and the pressure harmonics, and to determine the number of cycles required for a charge of gas to pass through the combustor. Additional radiation measurements will be carried out in order to shed further light on the ignition and combustion processes in the combustor.

Time permitting, the effect of the dimensions of the mixing chamber and the tail pipe will be investigated. Finally, the modeling effects on the pulsed combustors will continue.

References

1) R. B. Price, I. R. Hurle and T. M. Sugden, "Optical Studies of the Generation of Noise in Turbulent Flames," 12th Symposium (International) on Combustion, Poitiers, France, pp 1093-1102, 1968.

2) A. G. Gaydon and H. G. Wolfhard, "Flames, Their Structure, Radiation and Temperature," Chapman and Hall Ltd, London 1970.

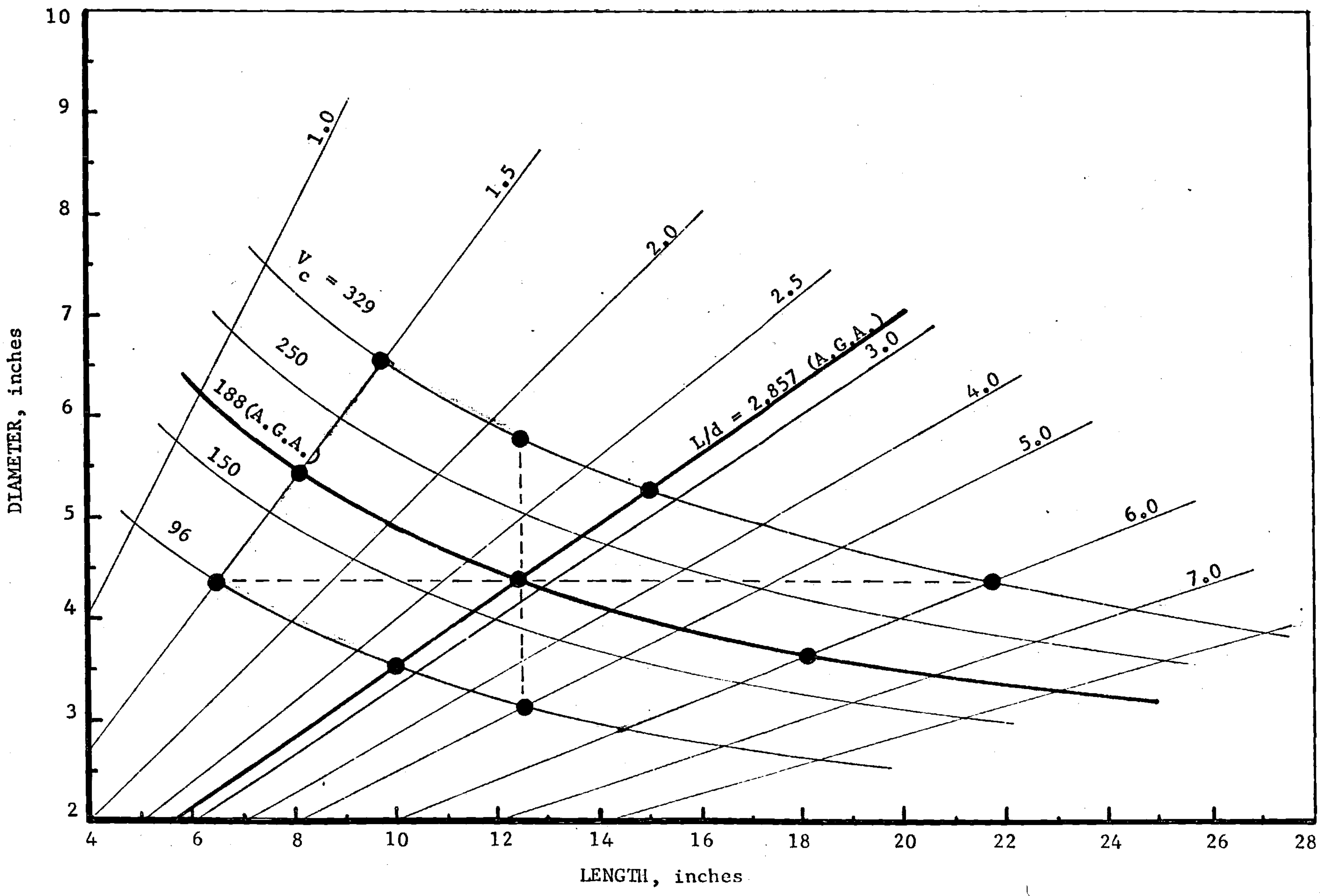
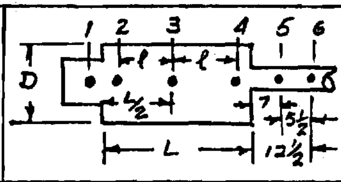
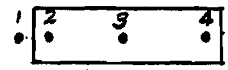
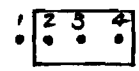
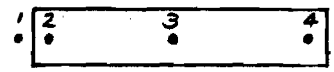
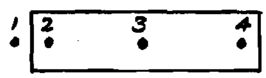
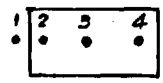
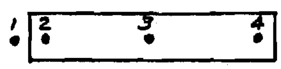
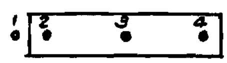
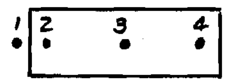
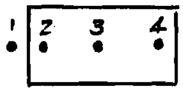
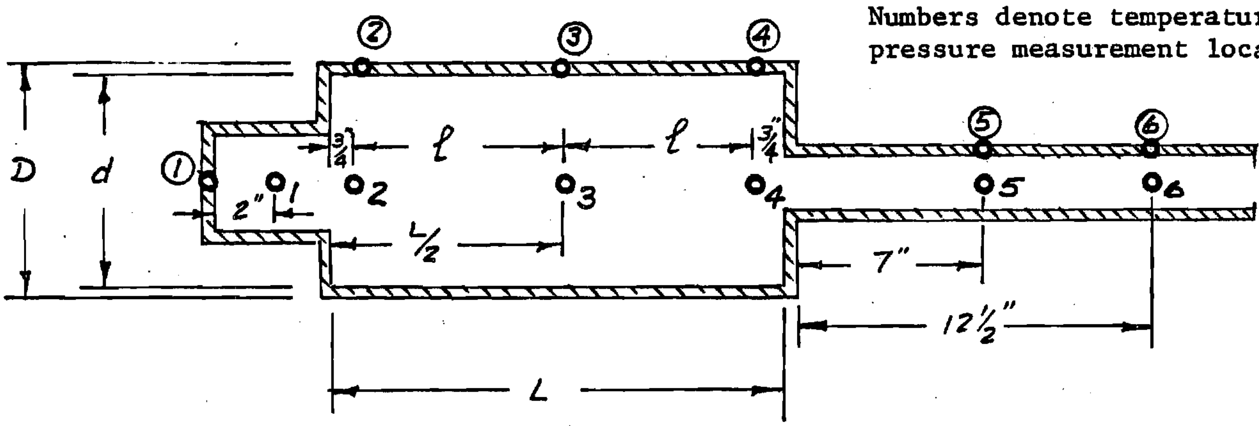


Fig. 1. Range of Investigated Combustor Configurations

DESCRIPTIONS OF THE TESTED COMBUSTORS

Index No.	Length L (inches)	Outer Diameter D (inches)	Inner Diameter d (inches)	Volume V (inches^3)	L/d		Measuring Points Distance ℓ (inches)
1	12 7/16	5	4 5/16	181.67	2.88		5 8/16
2	6 1/2	5 1/16	4 5/16	94.94	1.51		2 1/2
3	21 7/8	5	4 5/16	319.52	5.07		10 3/16
4	10 1/16	4 1/16	3 7/16	93.39	3.90		4 5/16
5	15	6	5 1/8	309.43	2.93		6 3/4
6	8 3/16	6	5 3/8	185.78	1.52		3 6/16
7	18 1/8	4 1/16	3 9/16	180.67	5.09		8 5/16
8	12 1/2	3 13/16	3 1/8	95.87	4.00		5 1/2
9	12 1/2	6 5/8	5 7/16	290.27	2.30		5 1/2
10	9 3/4	7	6 3/16	293.17	1.58		4 1/8



Numbers denote temperature and pressure measurement locations

Fig. 2. Combustion Configuration Tested.

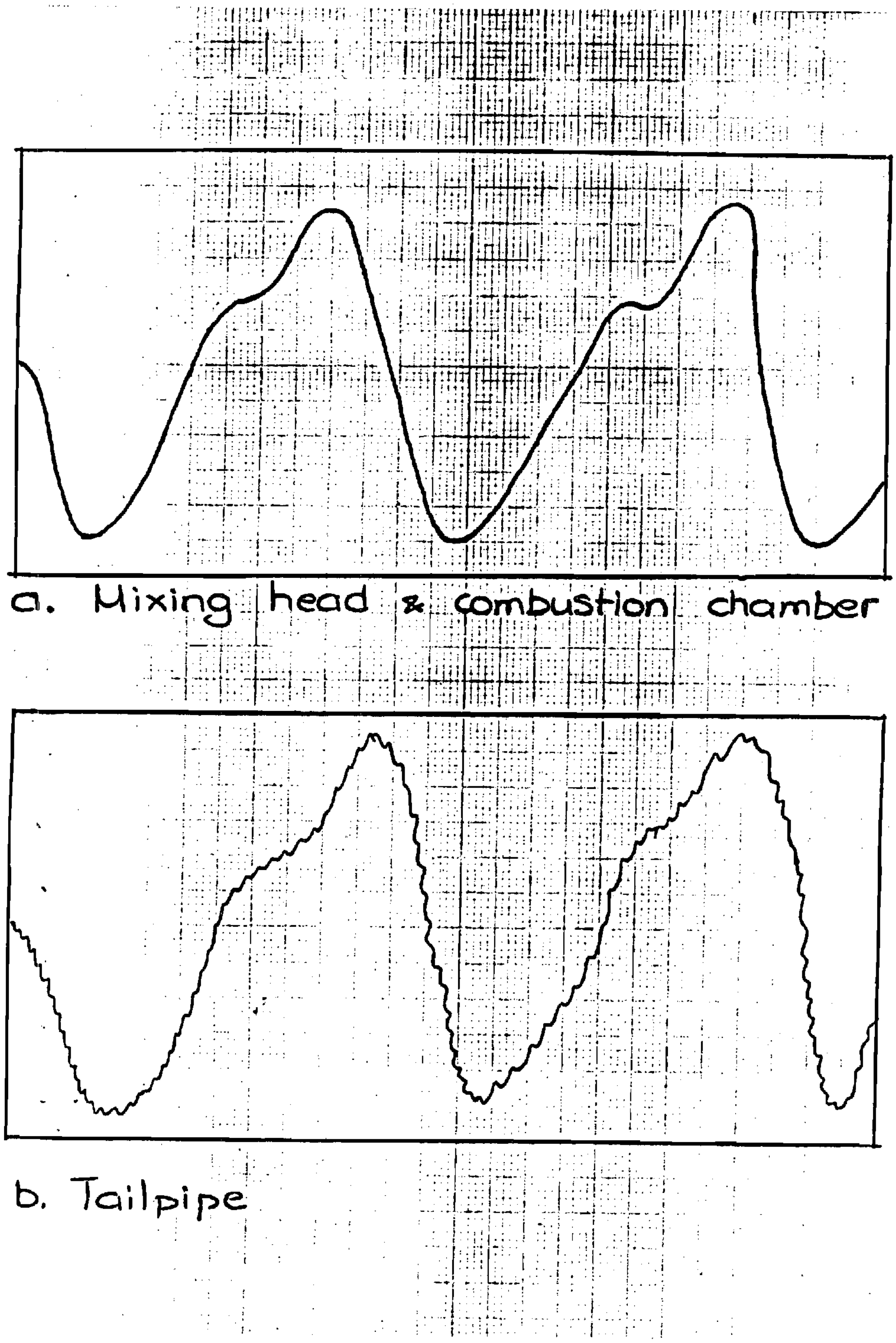


Fig. 3. Sample Pressure Traces from Combustion Chamber and Tail Pipe.

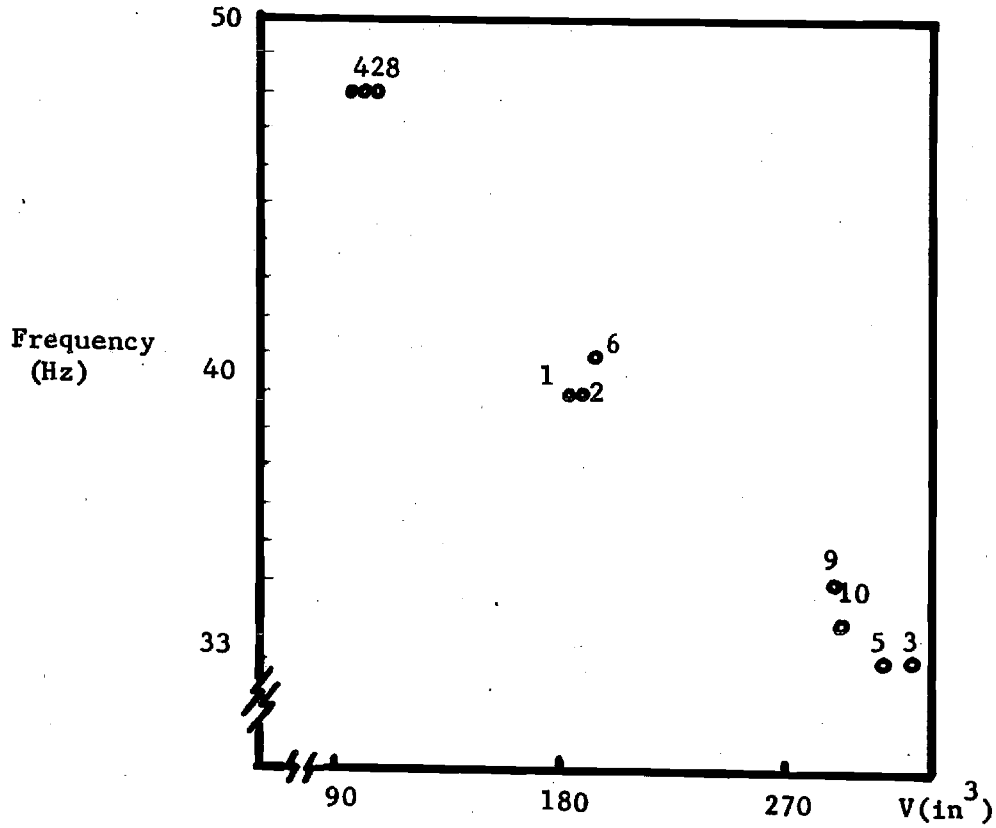
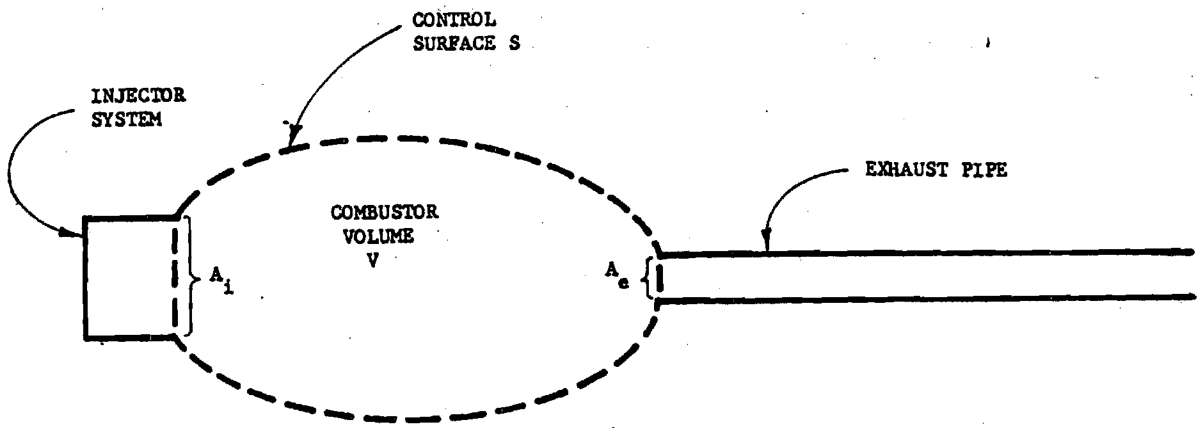


Fig. 4. Correlation of the Measured Frequencies with the Combustors Volumes.

ANALYTICAL CONSIDERATIONS

USING THE FOLLOWING BURNER MODEL



THE FOLLOWING RESULTS WERE OBTAINED

$$\alpha_a = k_{i_a}\bar{c} = \left(\frac{\gamma\bar{p}}{\ell}\right)\left\{\left(\frac{A_i}{A_c}\right)Y_{i_r} + \left(\frac{A_e}{A_c}\right)Y_{e_r}\right\} - (\gamma - 1)R_r \sim$$ Measure of initial amplification rate

$$\alpha_d = k_{i_d}\bar{c} = \left(\frac{\gamma\bar{p}}{\ell}\right)\left\{\left(\frac{A_i}{A_c}\right)Y_{i_r} + \left(\frac{A_e}{A_c}\right)Y_{e_r}\right\} \sim$$ Measure of decay rate after fuel was turned off

WHERE

$p' \sim e^{\alpha t + i\omega t}$

$R = Q'/p' \sim$ response of the combustion process

$\ell = V/A_c \sim$ characteristic length of the combustor

α_a and $\alpha_d \sim$ measured, exponential amplification and decay rates

FROM THE ABOVE RELATIONSHIPS ONE OBTAINS

$(\gamma - 1)\, R_r = \alpha_d - \alpha$

WHICH DESCRIBES THE DRIVING BY THE COMBUSTION PROCESS

Fig. 5. Results of Analytical Model.

ANALYTICAL CONSIDERATIONS (CONTINUES)

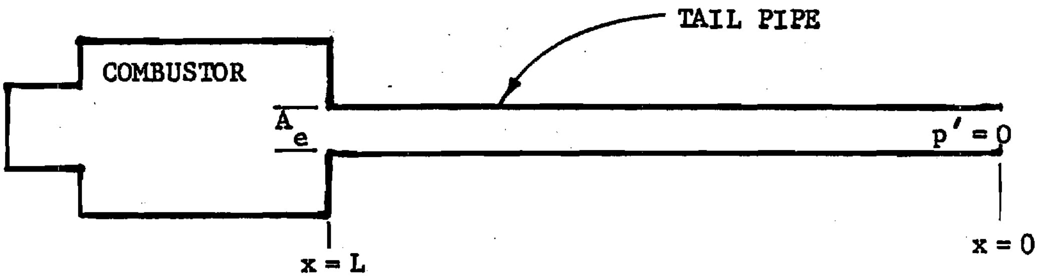
DETERMINATION OF THE FREQUENCY OF OSCILLATIONS

The Model Also Produced the Following Relationship:

$$V\omega = A_e Y_{e_i} / A_c \tag{1}$$

where $Y_{e_i} = \mathrm{Im}\left\{ (u'/p')_{\text{combustor exit}} \right\}$ (2)

To determine Y_{e_i}, consider the wave propagation process in the tail pipe:



Solutions: $p' = \epsilon \sin(\omega x/\bar{c})$; $u' = i(\epsilon/\bar{\rho}\bar{c}) \cos(\omega x/\bar{c})$ (3)

Hence,

$$Y_e = (u'/p')_{x=L} = i/(\bar{\rho}\bar{c} \tan(\omega L/\bar{c})) = Y_{e_i} \tag{4}$$

Substitute (4) into (1) to get

$$V\omega / A_e \bar{c} = (\tan(\omega L/\bar{c}))^{-1} \tag{5}$$

which shows that

$$\omega = f(A_e, V, \bar{c}, L) \tag{6}$$

Comments

(1) In our experiments to date only V was varied, indicating that the experimental trends agree with Eq. (6).

(2) When the tail pipe is very short (i.e., $L/\lambda << 1$) and the combustor resembles a Helmholtz resonator, Eq. (5) yields $\omega = \bar{c}(A_e/VL)^{1/2}$ which is the well known Helmholtz frequency.

Fig. 6. Results of Analytical Model (Cont'd).

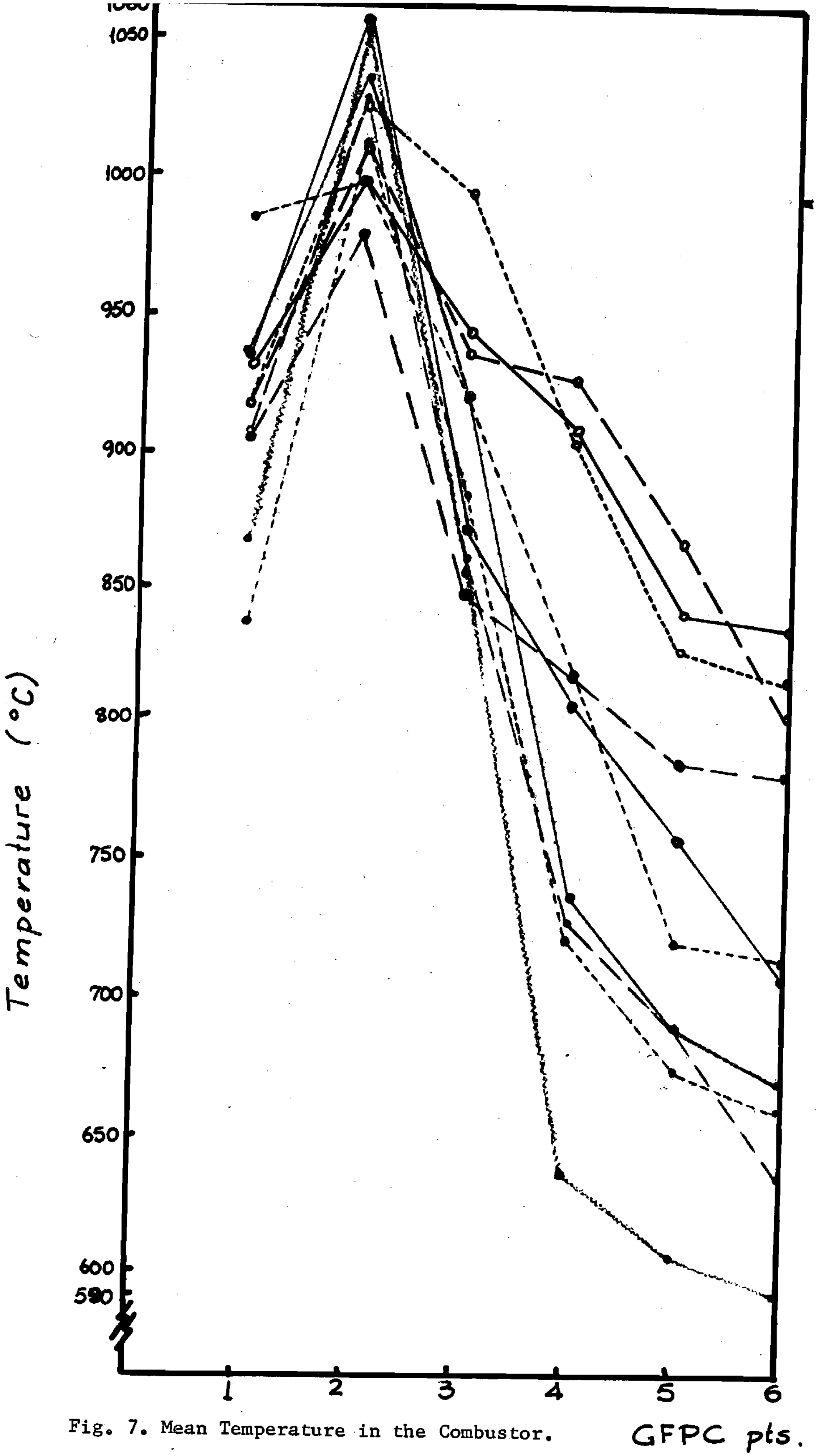


Fig. 7. Mean Temperature in the Combustor.

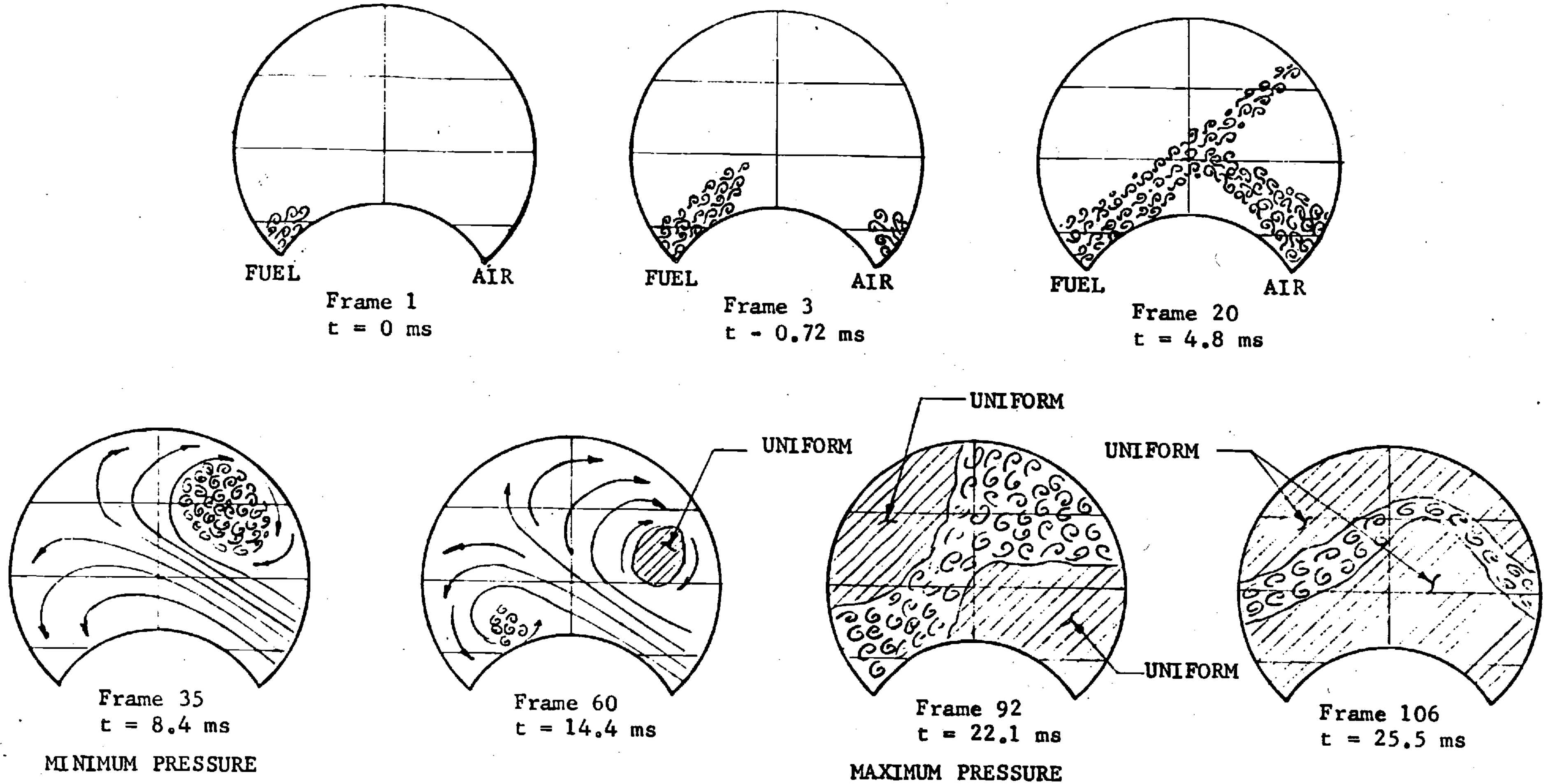


Fig. 8. SELECTED FRAMES FROM THE SHADOW VISUALIZATION MOVIES. COMBUSTION FREQUENCY, 40 Hz; 106 FRAMES PER CYCLE: 0.25 ms BETWEEN FRAMES.

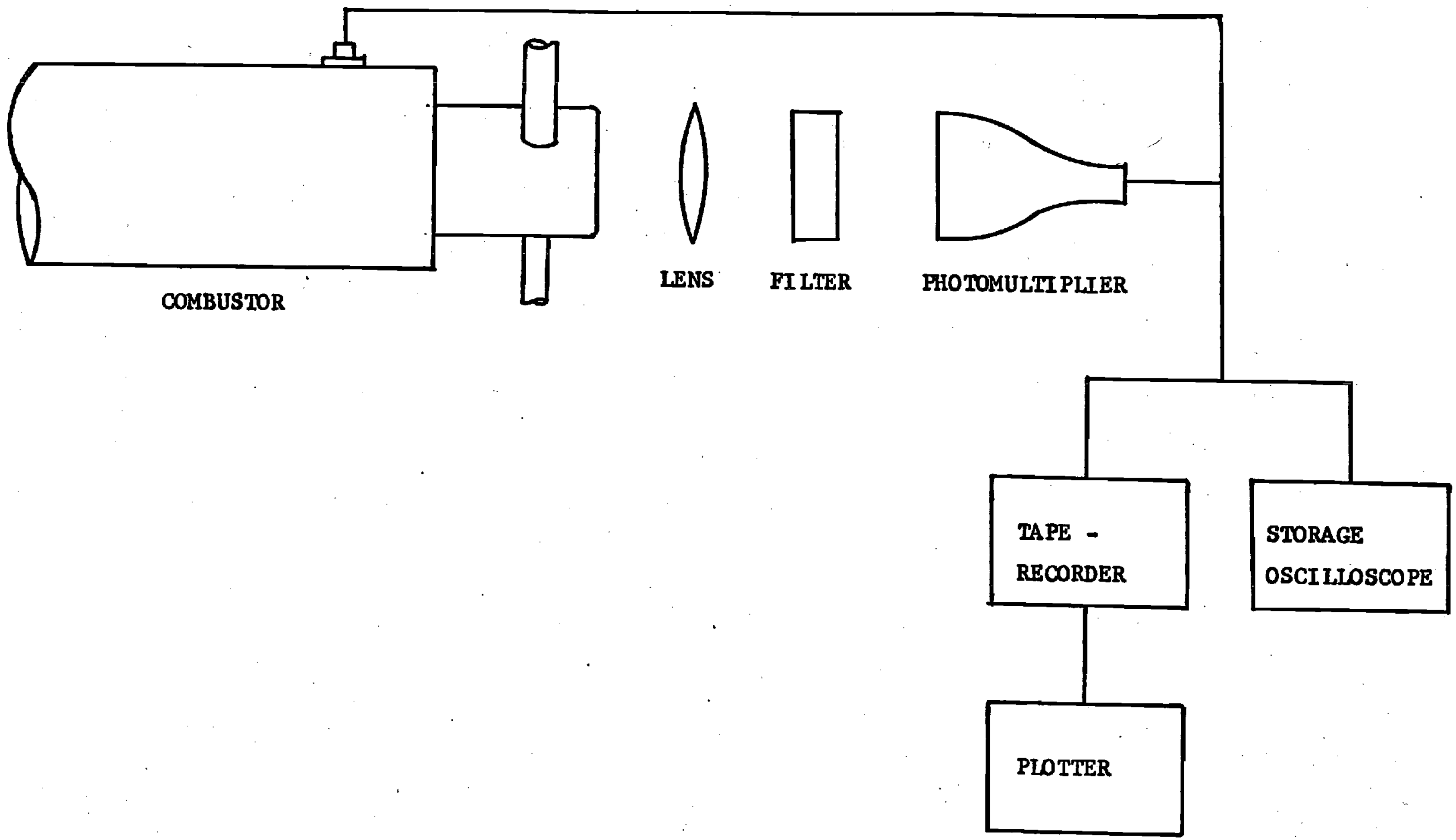
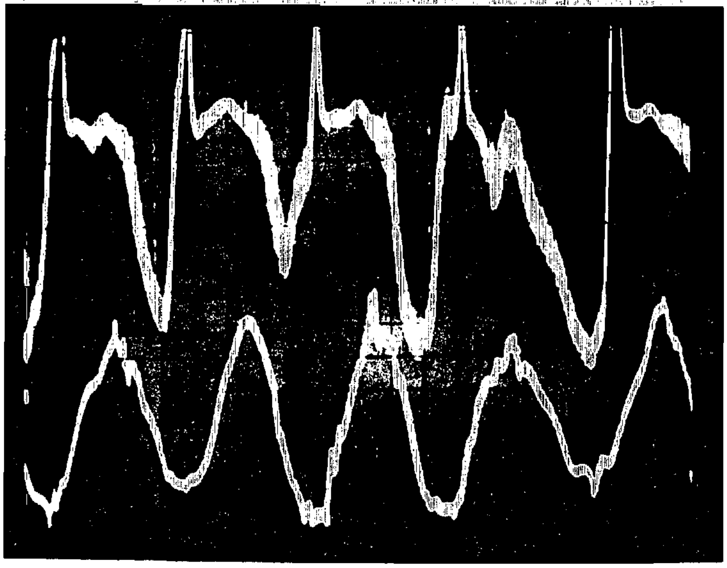


Fig. 9. RADIATION MEASUREMENT SYSTEM

Fig. 10. C-C RADIATION AND
PRESSURE MEASUREMENT

RADIATION

PRESSURE

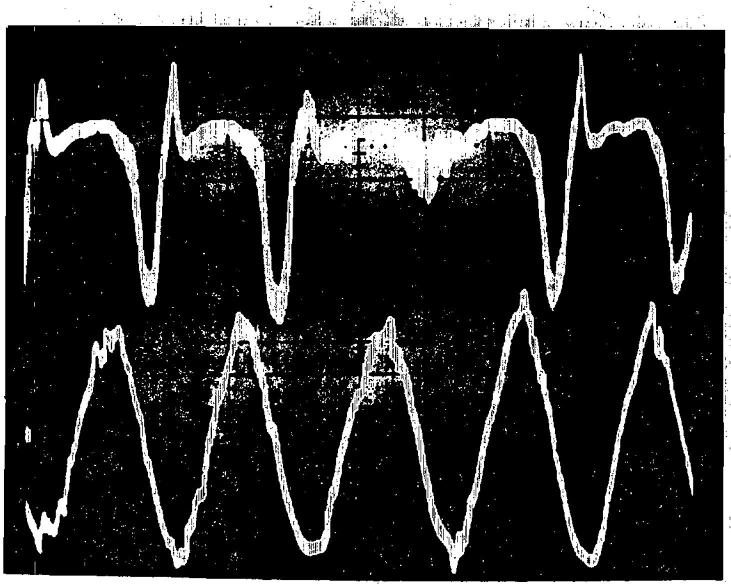


LEAN LIMIT

— 0 line

RADIATION

PRESSURE

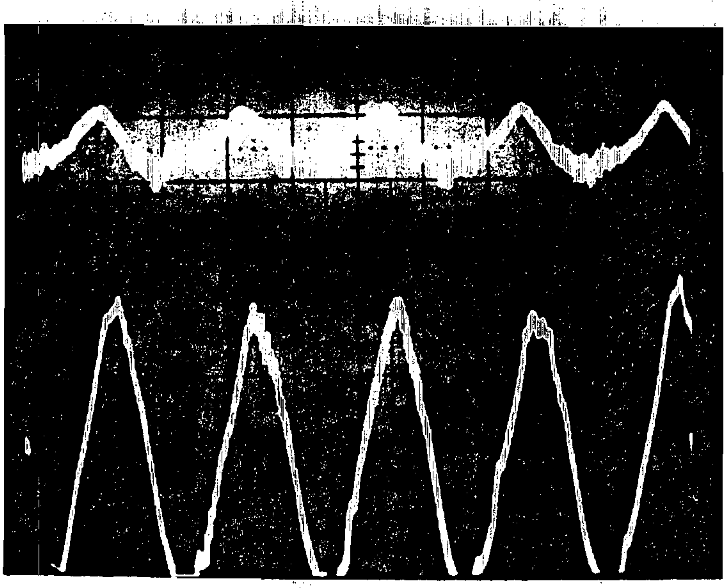


INTERMEDIATE

— 0 line

RADIATION

PRESSURE



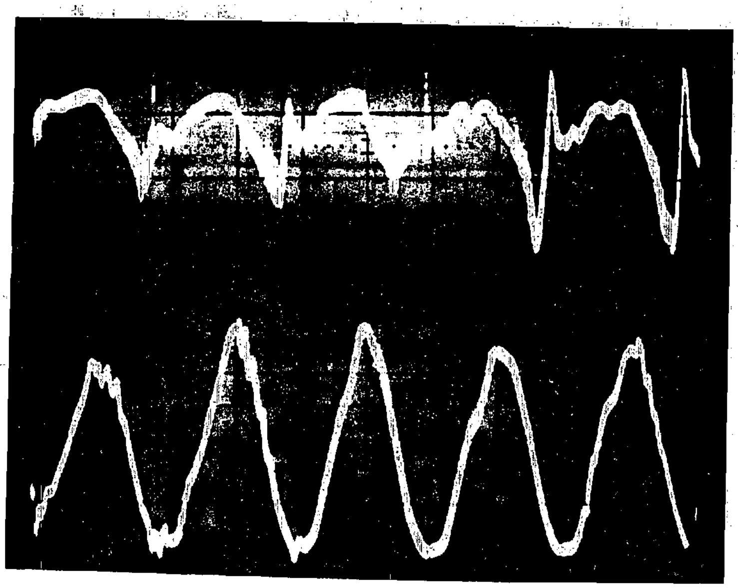
RICH LIMIT

— 0 line

PRESSURE MEASUREMENT

RADIATION

PRESSURE

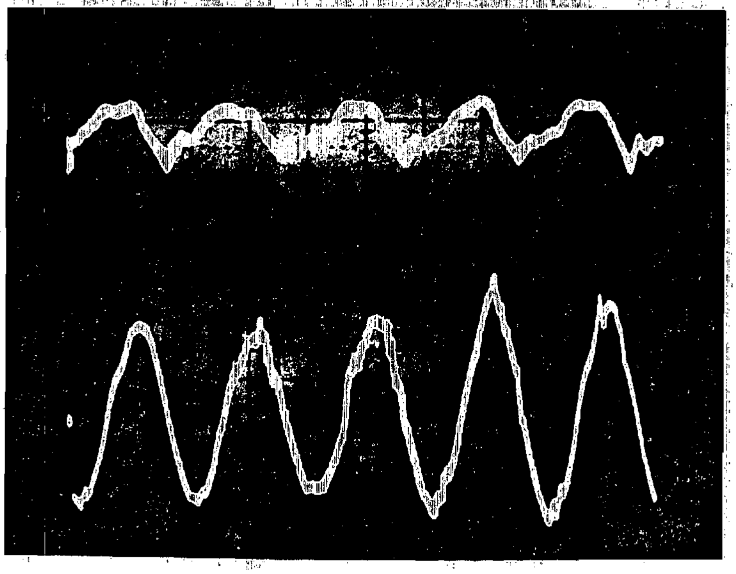


— 0 line

LEAN LIMIT

RADIATION

PRESSURE

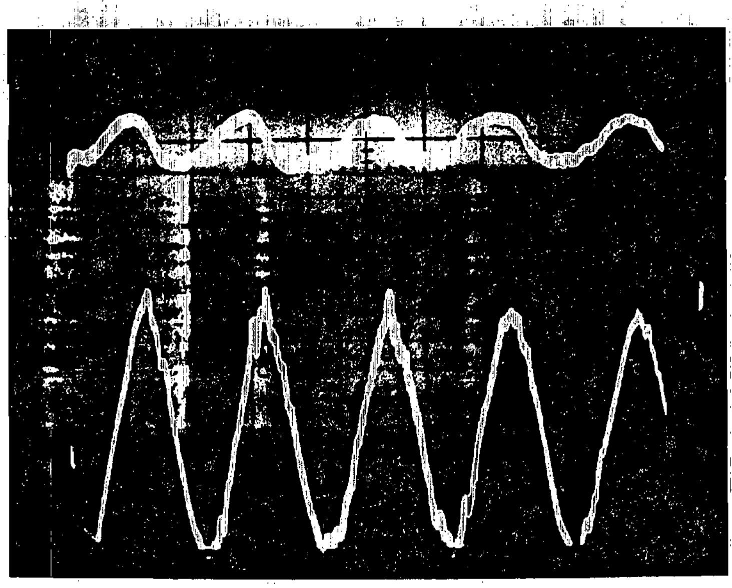


— 0 line

INTERMEDIATE

RADIATION

PRESSURE



— 0 line

RICH LIMIT

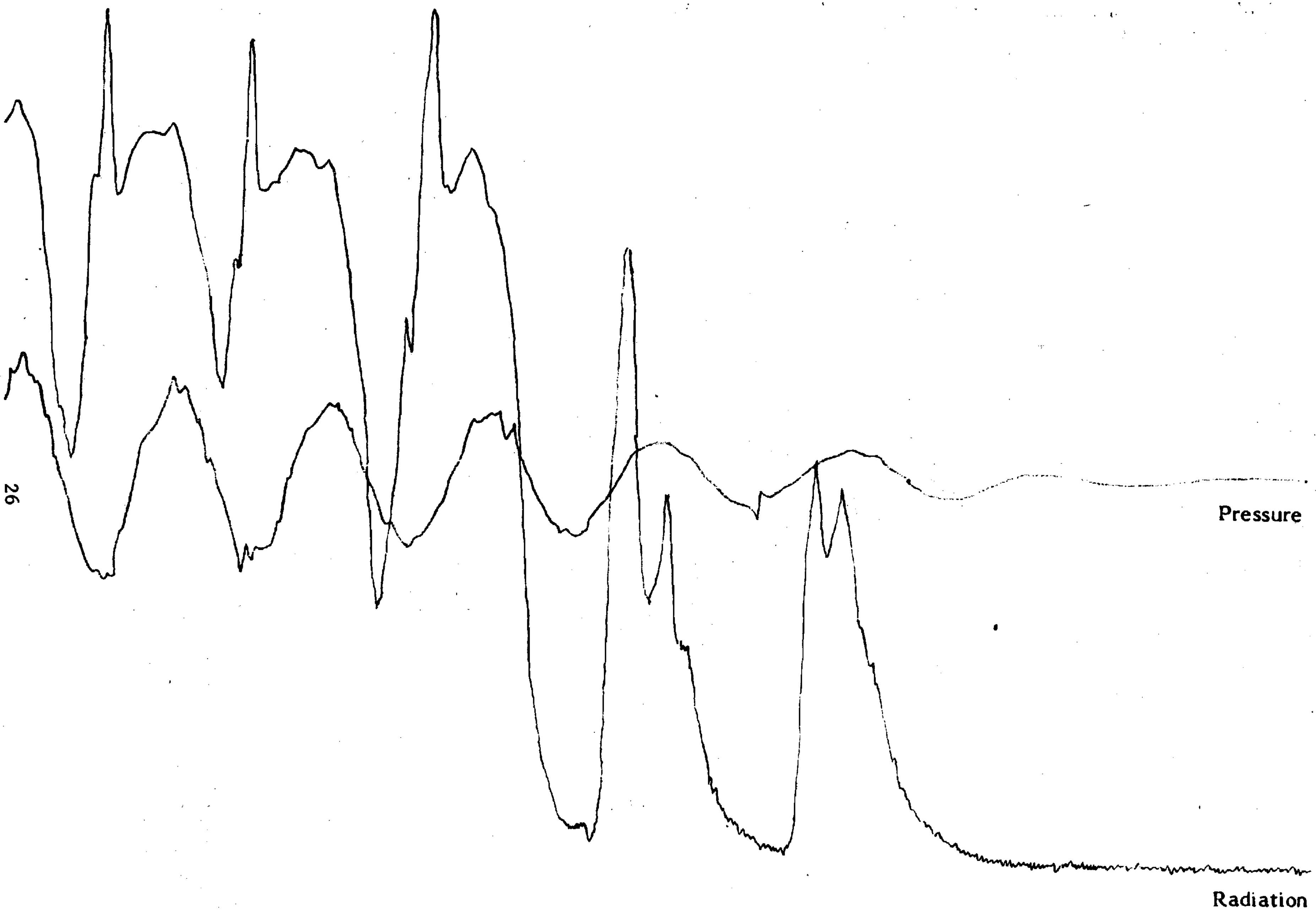


Fig. 12. C-C Radiation and Pressure During Shut-Off

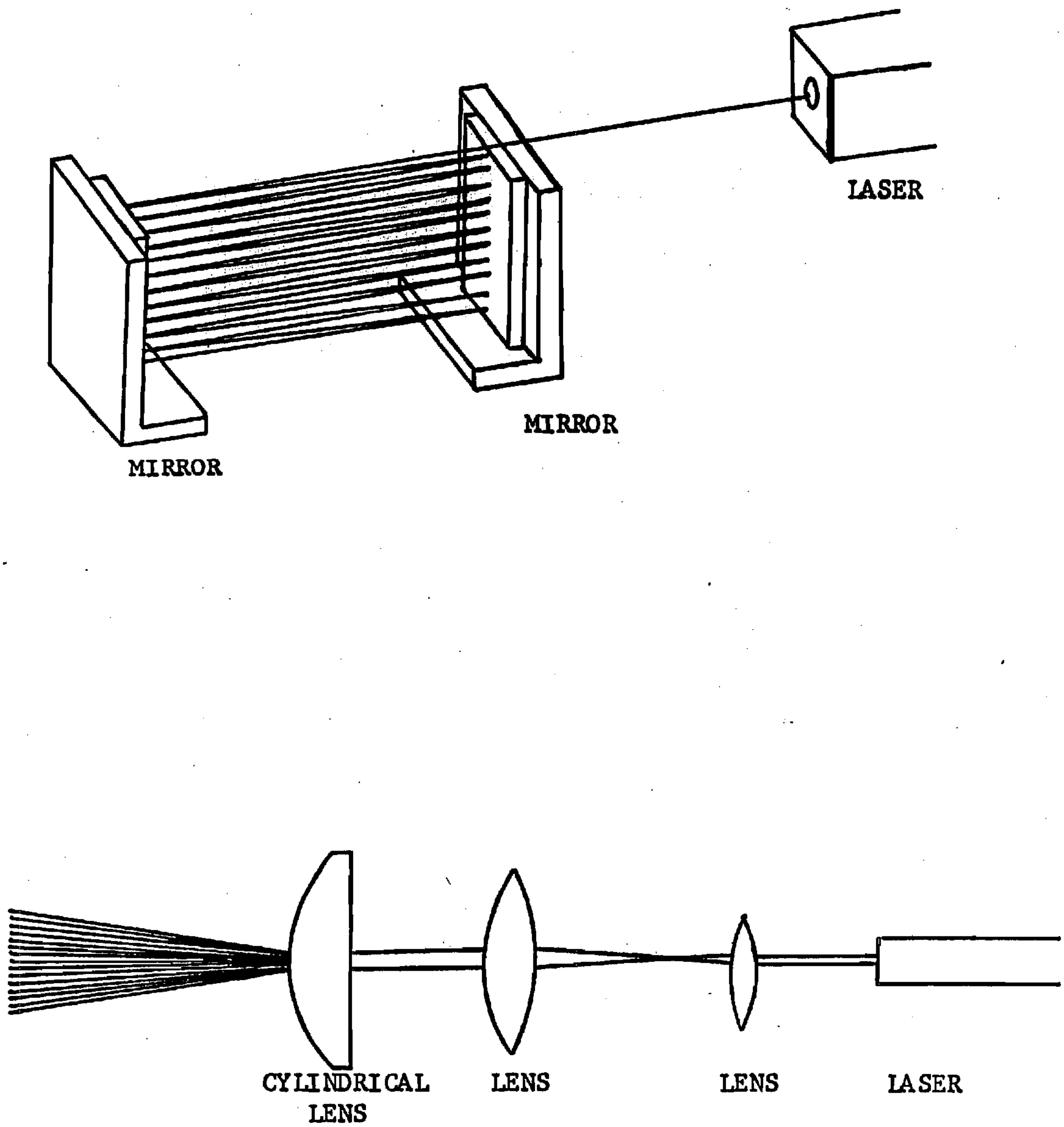


Fig. 13. Laser Sheet for Flow Visualization

GRI-86/0051

PULSATING BURNERS

CONTROLLING MECHANISMS AND PERFORMANCE

ANNUAL REPORT

(December 1984 - November 1985)

Gas Research Institute
8600 West Bryn Mawr Avenue
Chicago, Illinois 60631

Pulsating Burners - Controlling Mechanisms and Performance

Annual Report
December 1, 1984 - November 30, 1985

Prepared by

B. T. Zinn, B. R. Daniel and J. I. Jagoda

School of Aerospace Engineering
Georgia Institute of Technology

For

Gas Research Institute
Grant No. 5083-260-0873
GRI/85-0032

GRI Project Manager
James A. Kezerle
Combustion

January, 1986

GRI DISCLAIMER

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. 86/0031	2.	3. Recipient's Accession No. 86/0031

4. Title and Subtitle

Pulsating Burners - Controlling Mechanism and Performance

5. Report Date

April 85 (approved)

6.

7. Author(s)

B. T. Zinn, B. R. Daniel and J. I. Jagoda

8. Performing Organization Rept. No.

9. Performing Organization Name and Address

School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332

10. Project/Task/Work Unit No.

E-16-662

11. Contract(C) or Grant(G) No.

(C) 5083-260-0873

(G)

12. Sponsoring Organization Name and Address

Gas Research Institute
8600 West Bryn Mawr Ave.
Chicago, IL 60631

13. Type of Report & Period Covered

Annual
Dec 1, 84 - Nov 30, 85

14.

15. Supplementary Notes

16. Abstract

Although gas fired pulsed combustors for home heating have now been on the market for a number of years, little is known about the physical and chemical processes which control the operation of these devices. It is the objective of this study to gain an understanding of these processes such as mixing, cycle to cycle reignition and flame propagation in the burner. Such an understanding would permit a more rational approach towards the design of future combustors. Eleven combustors with different lengths, diameters and volumes have been constructed and tested. Mean temperatures and acoustic pressures were recorded and the exhaust gases analyzed for concentrations of CO_2, CO, O_2 and NO_x. All combustors performed well for fuel-air ratios between .6 and 1.1. This included one combustor in which the step between the mixing and combustion chambers was eliminated. The combustion chamber length and diameter had no influence on the combustor characteristics as long as the combustor volume remained fixed. An increase in volume, on the other hand, caused the frequency and dB levels of the pulsations and the mean temperatures to decrease. The combustion efficiencies for all combustors was very close to 100% except near the rich limit which appears to be mixing controlled. The CO and NO_x concentrations in the exhaust were of the order of 30-50 ppm for all combustors tested.

17. Document Analysis a. Descriptors

Pulse Combustor

b. Identifiers/Open-Ended Terms

Mixing, Reignition, Visualization, Radiation Measurements, Performance

c. COSATI Field/Group

Combustion

18. Availability Statement:	19. Security Class (This Report) Unclassified	21. No. of Pages
	20. Security Class (This Page) Unclassified	22. Price

(See ANSI-Z39.18) See Instructions on Reverse OPTIONAL FORM 272 (4-77) (Formerly NTIS-35) Department of Commerce

RESEARCH SUMMARY

Title	Pulsating Burners - Controlling Mechanisms and Performance
Contractor	Georgia Tech Research Institute
Contract Number	GRI Grant 5083-260-0873
Report Period	December 1984 - November 1985 Annual Report
Principal Investigator	B. T. Zinn, B. R. Daniel and J. I. Jagoda
Objective	The objective of this study is to gain an understanding of the fundamental processes, such as mixing and cycle to cycle reignition, which control the operation of gas fired pulse combustors. An analytical model is to be developed which will provide a rational procedure for the design and scaling of these burners.
Technical Perspective	In spite of the fact that gas fired pulse combustors for home heating have now been on the market for a number of years, little is known about the physical and chemical processes which control the operation of these devices. Of particular interest are the mixing of fuel and air, cycle to cycle ignition and the nature of the flame propagation in the burner. Such information is necessary for improving the operational characteristics of existing pulsating combustors and for guidance in the development of new burners for increased capacity or novel applications. Furthermore, the acquired insight will

be used to guide the development of a theoretical model for predicting the behavior of pulsating combustors. The availability of such a model would permit the replacement of the costly empirical trial and error methods used to date for the design and scaling of pulsed combustors by a more rational approach.

Results

During this contract year detailed performance measurements were carried out for different combustors in order to determine the effect of the fuel/air ratios (Φ) and various combustor dimensions on the operation of the pulse combustor. All combustors operated well for Φ's between about .6 and 1.1. The lower limit is close to the limit of flammability of the methane-air mixture while the upper limit seems mixing controlled. The pulse frequency is independent of Φ while the dB level is maximized at stoichiometric. The mean axial temperature distribution, which reaches its maximum near the mixing to combustion chamber transition, increases with Φ.

Combustion chamber diameters and lengths do not significantly affect the combustor performance. However, an increase in combustor volume results in a reduction in pulsating frequency and dB level indicating that the combustor behaves as a Helmholtz resonator. The influence of the combustor volume on the dB level also resulted in higher fuel and air flow rates for given valve settings in the smaller combustor. The acoustic pressure oscillations are characterized by constant frequencies and some cycle to cycle variations in amplitude.

Coordination between shadowgrams and radiation measurements confirmed previous Schlieren results that "cycle to cycle" ignition occurs immediately after the fuel and air jets impinge upon one another. High speed shadowgrams near the limits of the combustor operation revealed significant differences in the timing of the fuel and air injection and mixing compared to the combustor operations under optimal conditions.

<u>Technical Approach</u>

As a first step, a parametric study is being carried out using steel combustors in order to determine the influence of the combustor geometry and fuel air ratio on its performance and efficiency. Selected burners have been and are being fabricated in pyrex and quartz and their flow field investigated using high speed cinematography Schlieren/shadowgraphy, stream line and mixing visualizations as well as laser Doppler velocimetry (LDV). Lastly, C-H and C-C spectroscopy is being used in the determination of the timing, location and rate of heat release during the combustion cycle. A linear and, if necessary, a non-linear theoretical model of the combustor is being developed to provide a basis for future pulsating combustor design and scaling.

<u>Program Plan</u>:
The program is divided into three distinct tasks outlined below:

Task I - Experimental Investigation
- A Performance
- B Flow Visualization
  - a) streamline visualization
  - b) shadow/Schlieren
- C Mixing Visualization

C LDV

E C-H & C-C Spectroscopy

Task II - Analytical Study

Task III - Reporting

Project Implications

Research in the second year of this contract has consisted of an extensive study of combustion chamber size, shape, and length on performance of a relatively small (nominal 50,000 Btu/hr) pulse combustor. The research will be continued for a third year to complete the analysis of these data and to study flow within the pulse combustor with laser Doppler velocimetry (LDV). Differences in operation between optimal and limit conditions will be studied. Results from this research have indicated a need for similar data from much larger pulse combustors. GRI will acquire these data in a new contract with Forbes Energy Engineering to study operation of pulse combustors up to two orders of magnitude larger in heat input rating. Comparison of data from Georgia Tech and Forbes should yield insights for pulse combustor scaling.

GRI Project Manager
James A. Kezerle
Manager, Combustion
Physical Sciences Department

INTRODUCTION

The objective of this study is to gain insight into the fundamental processes responsible for the operation of gas fired pulsed combustors and to develop an analytical model capable of predicting the performance characteristics of new pulsed combustor designs. Furthermore, the model will consider the effect of scaling upon combustor performance. To this end, the effects of a number of geometrical combustor parameters, such as L/D ratio, combustor volume and exhaust pipe length and diameter, upon the combustor performance are under investigation. Also, the interactions between the pulsed flow field and combustion processes are being studied. Special emphasis is placed on determining the source and location of the cyclic ignition and following the flame spread in the combustor. The streamlines in the flow field and the mixing of fuel and air are being visualized and recorded. Velocities are measured using LDV. An analytical model is being developed which will predict the performance of combustors having different geometries and scales. The insights gained from the above experiments will be used in the development of the model which will, in turn, be tested against further experimental data. It is, thus, anticipated that this study will enable the industry to abandon the currently used empirical approach in the design and development of pulsed combustors in favor of a rational design procedure based upon dependable model predictions.

Program Plan

The program is divided into three major tasks as outlined below:

Task I - Experimental Investigation

A. Performance Evaluation. The performance of a number of combustors of different geometries (i.e., different L/D, volumes, tail pipe lengths, etc.) is being investigated using temperature, pressure and combustion efficiency measurements.

For each configuration, the performance is evaluated over a range of air/fuel ratios and fuel loadings.

B. High Speed Cinematography. This technique is used to determine the locations of cycle to cycle ignition and the shape and motion of the flame.

C. Flow Visualization. Stream lines are being investigated by recording the tracks of seed particles moving through a laser light sheet. This process is repeated with the laser sheet at different combustor locations. Refractive index gradients caused by the flame front or by pockets of hot and cold gases are visualized using Schlieren and shadowgraphy.

D. Mixing Visualization. Mixing patterns are being recorded photographically by heavily seeding either the fuel or the air and illuminating the transparent combustor using a laser light sheet. Again, the visualization is repeated with the laser sheet at different combustor locations.

E. LDV. A 2-D Laser Doppler Velocimeter has been set up and tested, and is used to measure velocities at selected stations in the mixing and combustion chamber and in the tail pipe. The data acquisition system previously developed is being modified to permit ensemble averaging over a number of cycles. A special combustor is being fabricated in order to avoid the problem of beam displacement due to the cylindrical walls.

F. C-H & C-C Spectroscopy. In this part of the study radiation from the combustor is passed through the respective filters and its intensity measured using a photomultiplier. The radiation measurements are then related to combustion intensities. These are then compared with the phase measurements of mixing as determined from the high speed shadowgrams and with the instant of ignition as recorded using high speed, low sensitivity Schlieren.

Task II - <u>Analytical Study</u>

A theoretical model which describes the performance of the investigated combustors is being developed. The model will incorporate the findings of the experimental phases of the program. The model will be linear and investigate the possible range of operating conditions of the burners.

Task III - <u>Reporting</u>

As per contract agreement.

PROGRESS AND RESULTS FROM PREVIOUS YEAR

During the previous year (Dec. '83 - Nov. '84) 10 steel combustors having different lengths, lengths to diameter ratios, diameters and volumes were designed and fabricated. The 10 combustors' geometries were chose to allow the investigation of the effect of the diameter the length and the volume of the combustion chamber on the performance of the pulse combustor system. In addition, one combustor with transparent quartz end plates and one all pyrex combustor for optical diagnostics were constructed. An exhaust gas train to determine the combustion product compositions and, thus, the combustion efficiencies and the concentrations of exhaust pollutants was designed and set up. A scheme for determining the combustion efficiencies from the exhaust gas analysis was developed and software was written to acquire temperatures, acoustic pressures and exhaust gas compositions and to determine the efficiencies of the combustors.

The optics for measuring C-C and C-H radiation and a high speed Schlieren and shadowgraphy system had been placed in operation as had a particle track visualization system.

All the combustors operated well. The frequency of pulsation was found to be a function of the volume of the combustion chamber indicating that the combustors operate as Helmholtz resonators. Visual observations in the all pyrex combustor showed that for this configuration most of the combustion actually takes place in the "mixing chamber". High speed Schlieren and shadowgrams visualized the incoming fuel and air jets, their mixing and combustion. Low sensitivity Schlieren was used to differentiate between the Schlieren markings due to hot/cold gas interfaces and those due to flame fronts. C-H and C-C radiation from the entire combustor were measured near the fuel rich and fuel lean limits and for the optimum operating conditions of the combustor. The latter corresponds to those used in the visualization studies. These measurements showed that the reaction does not cease at any time during a cycle of operation. Furthermore, it was observed that the magnitudes of the radiation fluctuations decreased as the fuel air ratio is increased. At the same time, the pressure amplitudes remained essentially unchanged. Finally, comparison of the shadowgram and radiation measurements indicated that both C-C and C-H radiation sharply increase at the instant in each cycle at which the new fuel and air jets first impinge. This suggests that the ignition of the new charges occurs at this instant.

PROGRESS AND RESULTS OBTAINED IN CURRENT YEAR

During the current year of a the project (Dec. '84 - Nov. '85) both performance testing and optical diagnostics on the pulse combustor were continued. A large decoupling chamber was added upstream of the air valve of the steel combustors. This permits the measurement of the mean air flow rates for comparison with the flow rates calculated from the exhaust gas analysis. An eleventh steel combustor whose mixing and combustion chamber diameters are the same was designed and constructed. In this combustor the step between the mixing and combustion chamber was effectively eliminated. A sample probe was fitted to the exhaust pipe of the steel combustor one quarter of the way between the combustion chamber and the decoupler (Fig. 1). The probe was connected via a heated line to the exhaust gas sample train. The CO, CO_2, O_2 and NO_x analyzers in the sample train were calibrated and the data reduction software used to calculate the combustion efficiency was thoroughly tested. The combustors were instrumented with thermocouples and pressure transducers mounted in an infinite tube configurations to determine mean temperatures and acoustic pressures at various locations in the steel combustors (Fig. 1). The combustor mean boost pressure was also determined.

The stepless combustor described above worked well and exhibited the same characteristics as a combustor of equal volume, but with a step. This suggests that the step does not significantly influence the combustion process. All eleven combustors were found to operate well with their frequency of pulsation being dependent only on the combustor volume for fixed mixing chamber and exhaust line dimensions. Detailed tests were carried out for combustors of different dimensions which were selected to permit the determination of the influence of combustion chamber length, diameter and volume on the combustor performance. During these tests temperatures and pressures were measured at various locations in the mixing chamber, the combustion chamber, the exhaust pipe and the decoupler (Fig. 1). Fuel and air flow rates were measured upstream of the flapper valves. At the same time, the concentrations of CO, CO_2, O_2 and NO_x in the exhaust gas were measured. From these the combustion efficiencies and fuel equivalence ratios were calculated. The latter were compared with the values for the equivalence ratio obtained from the fuel and air flow rate measurements. They agreed, generally, to within 1-2%. The range of operation of each tested combustor was established by varying the air flapper valve setting since the fuel flapper setting is fixed. As the air flapper gap was increased the air flow rate increased considerably. At the same time the fuel flow rate decreased slightly despite the fixed fuel valve setting (Fig. 2).

All combustors operated well at nondimensional fuel air ratios (Φ) between slightly rich of stoichiometric and about .6. While the lean limit of operation of the combustors lies close to the limit of flammability of a methane-air mixture the fact that the combustor does not operate well on the rich side of stoichiometric was thought to be due to either inadequate mixing or to problems in the air flapper valve. Since the fuel flapper valve setting is fixed, the air flow had to be reduced to yield a fuel rich mixture in the mixing chamber. This required the setting of a very small gap in which the flapper disc could move, which could result in significant pressure losses in the air valve. To overcome this the effective cross-section of the flapper was reduced by plugging some of the holes in the air intake, resulting in a wider gap setting for low air flow rates. These changes, however, did not significantly extend the operational limits of the combustor. The limit slightly rich of stoichiometric seems, thus, to be mixing controlled.

Very good performance was achieved for all conditions except near the operational limits. The frequencies of oscillation were independent of Φ (Fig. 3) while the dB levels increased slightly as Φ increased and then decreased somewhat near stoichiometric (Fig. 4). The mean temperature in the mixing chamber was found to be of the order of 1000^{o}C. It increased to a higher value at the entrance to the combustion chamber after which it dropped in the axial direction throughout the combustor and tail pipe (Fig. 5). All temperatures increased as the fuel air ratio approached unity. The combustion efficiency was determined to be nearly 100% for all combustors except near the rich limit where it dropped by 3-4% (Fig. 6). Correspondingly, CO levels were found to be of the order of 20 ppm except near the rich limit (Fig. 7). The NO_x levels were approximately 30 ppm at the lean limits, rose to about 60 ppm at stoichiometric before falling slightly near the rich limit (Fig. 8).

All the above described parameters were not noticeably affected by changes in the combustion chamber diameter or length as long as the chamber volume was kept constant. An increase in the combustion chamber volume, however, did result in a lower pulsating frequency (Fig. 3) and a lower dB level (Fig. 4). It is this reduction in dB level which caused a reduction in the fuel and air flow rates for given valve settings and fuel air ratios (Fig. 2). Mean temperatures throughout the burner were also higher the smaller the combustor volume (Fig. 5). The combustion efficiencies were close to 100% for all combustors but dropped most significantly near the rich limit for the smallest combustor (Fig. 6).

Acoustic pressures at various locations in the different combustors and at a number of fuel air ratios are presently being measured. The acoustic frequencies are very regular but fluctuations in amplitudes have been observed (Fig. 9). Special attention is being paid to the behavior of the pressure signal during combustor start-up and shut-down in order to determine the driving and damping characteristics of the pulse combustor.

Comparison of the shadowgraphy, Schlieren and C-C or C-H radiation results obtained largely in the previous year indicated that there is a pronounced increase in the radical concentration and, thus, probably the reaction rate when the fuel and air jets first impinge on each other. Cycle to cycle reignition of the new reactants coincide with the instant when new fuel and air first mix. Similar observations were made using the low sensitivity Schlieren set-up as described in last year's annual report. The ignition source for the new reactants may be expected to consist of entrained radicals left over in the mixing chamber from the previous cycle. In this connection it should be pointed out that it is well known that under certain conditions the entrainment rates of pulsating jets are considerably higher than those of steady jets.

Flow visualization using particle tracking were carried out using still and high speed cine-photography. Particle tracks were clearly visible showing the air entering the mixing chamber and the ensuing turbulent mixing. The overall flow patterns thus observed were similar to the ones seen in the shadow visualizations. However, the particle tracks were not as clear as the shadowgraph/Schlieren markings, since a significant part of the energy in the laser light sheet is reflected as it passes through the curved surfaces. The particles are also quickly swept out of the vertical laser light sheet in the axial, downstream direction.

Additional high speed shadowgraph movies are currently being obtained in order to investigate the fuel and air flow patterns and their mixing near the limits of flammability of the combustor. First observations obtained under conditions for which pulse combustion can only be maintained for some 10-20 secs after the spark plug is switched off indicate significant differences in the timing of the individual steps in the pulse combustion process such as fuel and air injection, mixing, the appearance of large regions of uniform combustion products etc. In particular, it was noted that while under regular conditions fuel and air jets enter at the beginning of each cycle into a mixer head filled with combustion products at uniform temperature with only a few reacting pockets in evidence, near the operational limit the fuel and air jets appear while the mixing chamber is still filled with what appears to be reacting pockets at different temperatures. This phenomenon will be further investigated during the coming year.

Due to personal difficulties encountered by the graduate student working on the analytical model, progress in this area was slow. Efforts concentrated on the derivation of the required wave equations, the modelling of the flapper valves and combustion process dynamics and the choice of an appropriate solution technique.

WORK PLANNED FOR THE COMING YEAR

During the next contract year the acoustic pressure measurements will be completed in all combustors over the full range of fuel air ratios. Special attention will be paid to the transient behavior of these pressures during start-up and shut-down which will permit the determination (or estimation) of the driving and damping characteristics of the combustor. For this purpose a single spark ignition system activated after a variable time delay by the fuel solenoid valve is being constructed to avoid interference by the continuous spark presently used with the pressure transient recordings during start-up.

Additional high speed Schlieren and shadowgram movies and C-C and C-H radiation measurements will be obtained to determine the mixing patterns at each phase in the cycle and the phase relationship between mixing and ignition for the combustors operating near their operational limits. These findings will be compared with those obtained while the combustor is operating under optimal conditions.

An additional, essentially cylindrical combustor fitted with flat windows along the curved walls will be constructed. This new unit will permit not only Schlieren and shadowgraphy from a side-on view but also facilitate better LDV measurements. LDV measurements will be carried out in order to map the complex flow field in the mixing and combustion chambers and in the tail pipe. This will not only permit a quantitative description of the flow field but also a determination of the extent of back flow in the various parts of the combustor and of the residence time of the charges in the pulse combustors. Finally, the modelling efforts on the pulse combustors will continue.

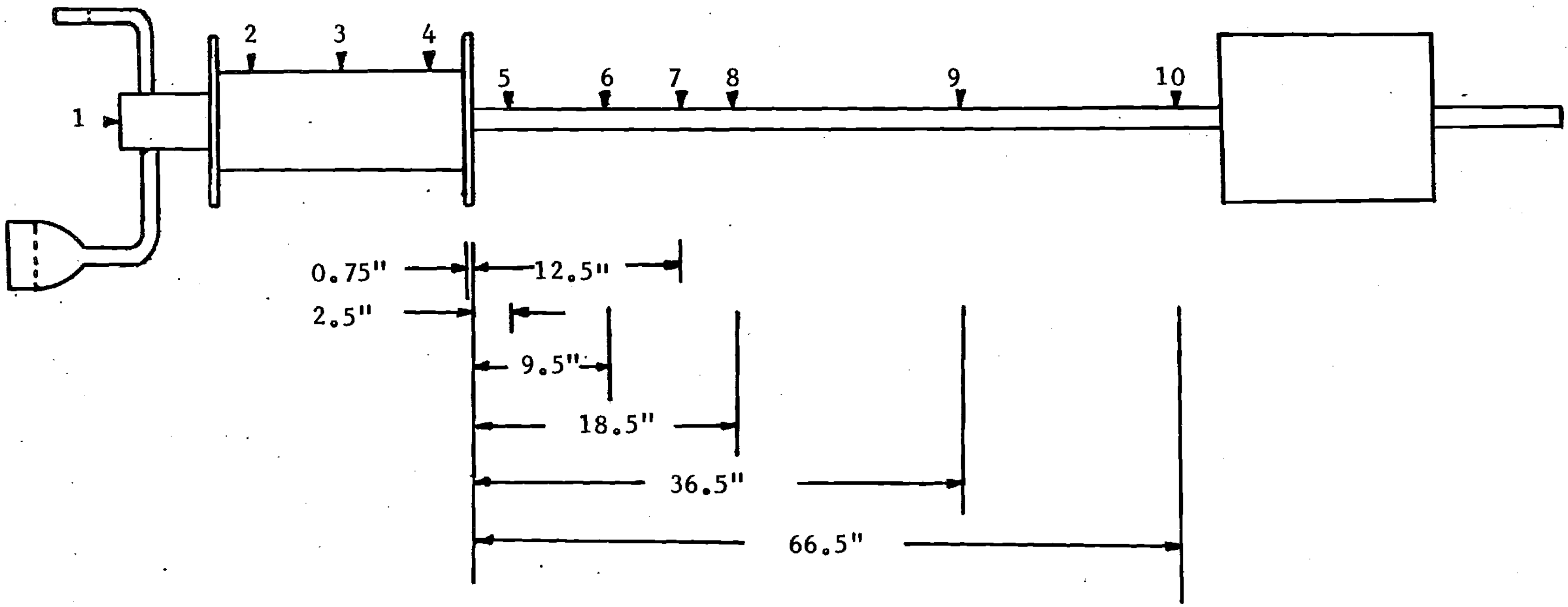


Figure 1. Location of Pressure and Temperature Measurement Positions in the Pulse Combustors.

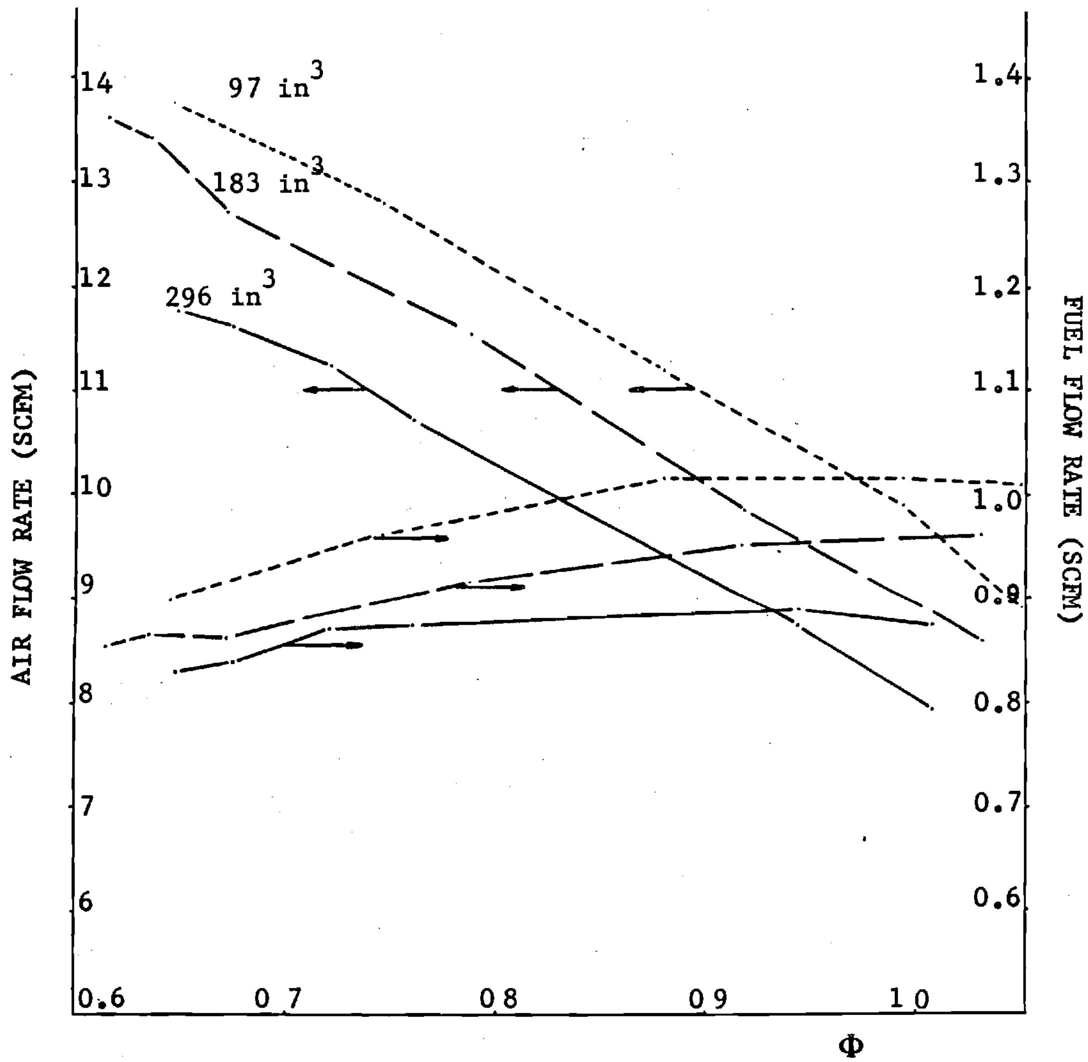


Figure 2. Fuel and Air Flow Rates vs. Fuel-Air Ratio for Combustors of Three Different Volumes.

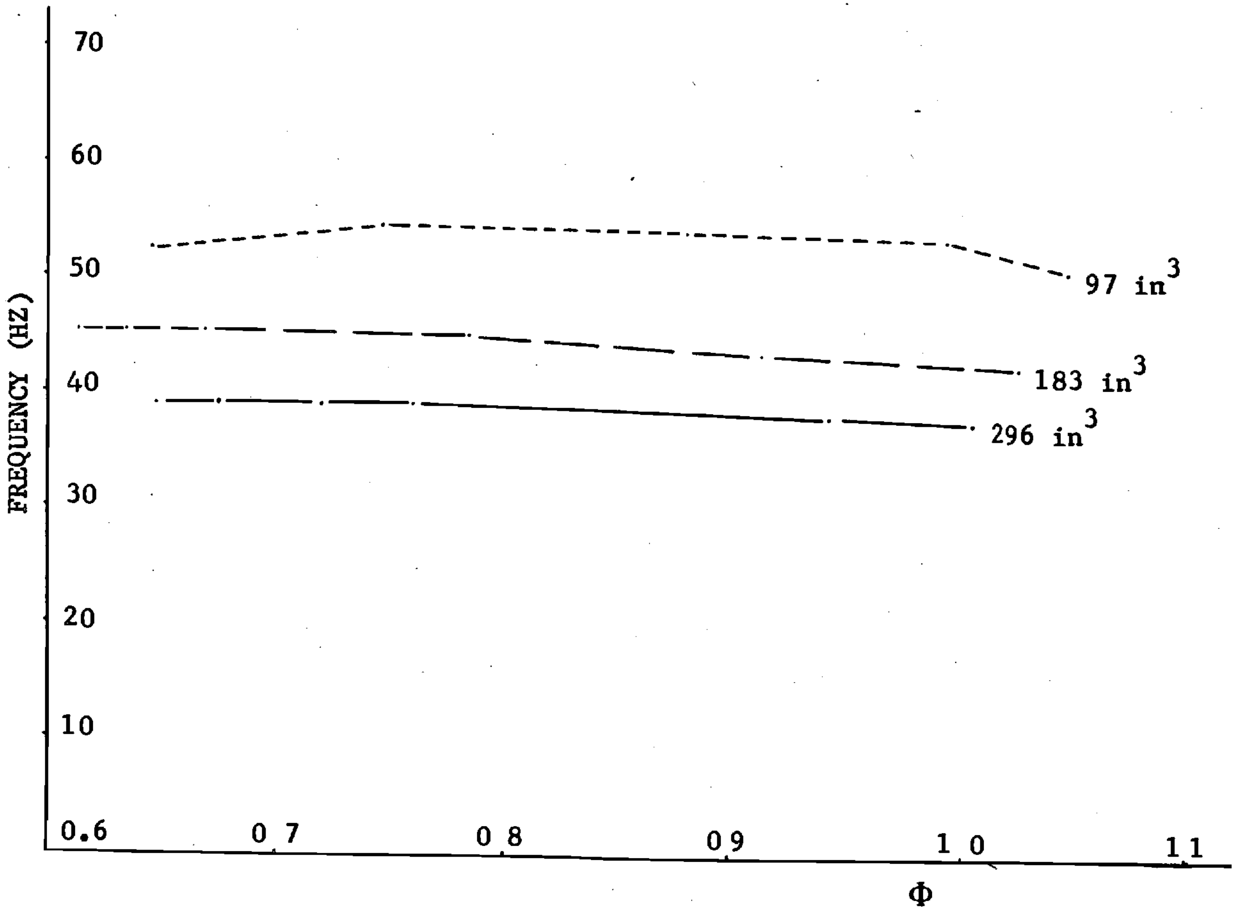


Figure 3. Frequency vs. Fuel-Air Ratio for Combustors of Three Different Volumes.

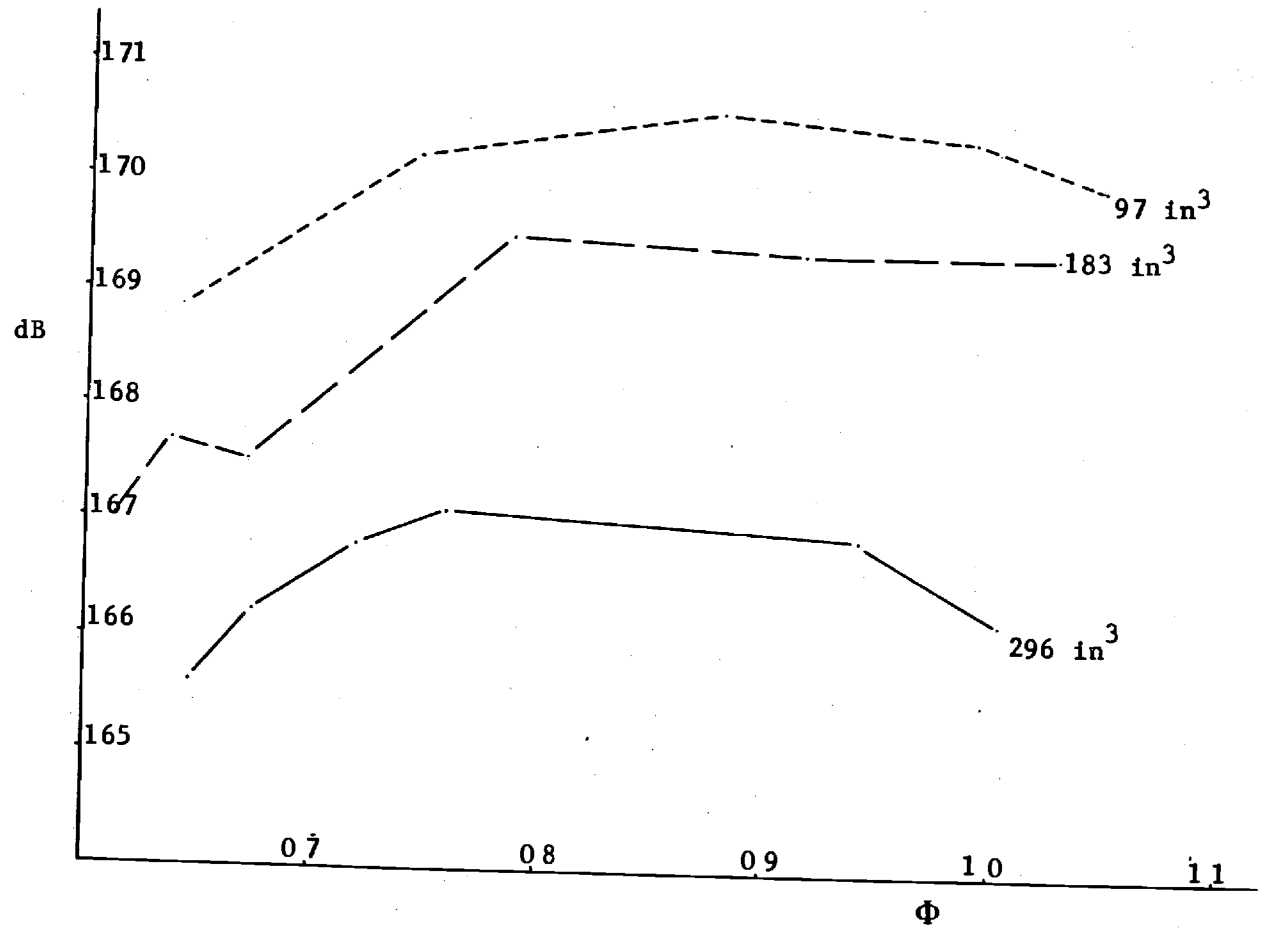


Figure 4. DB. level vs. Fuel-Air Ratio for Combustors of Three Different Volumes.

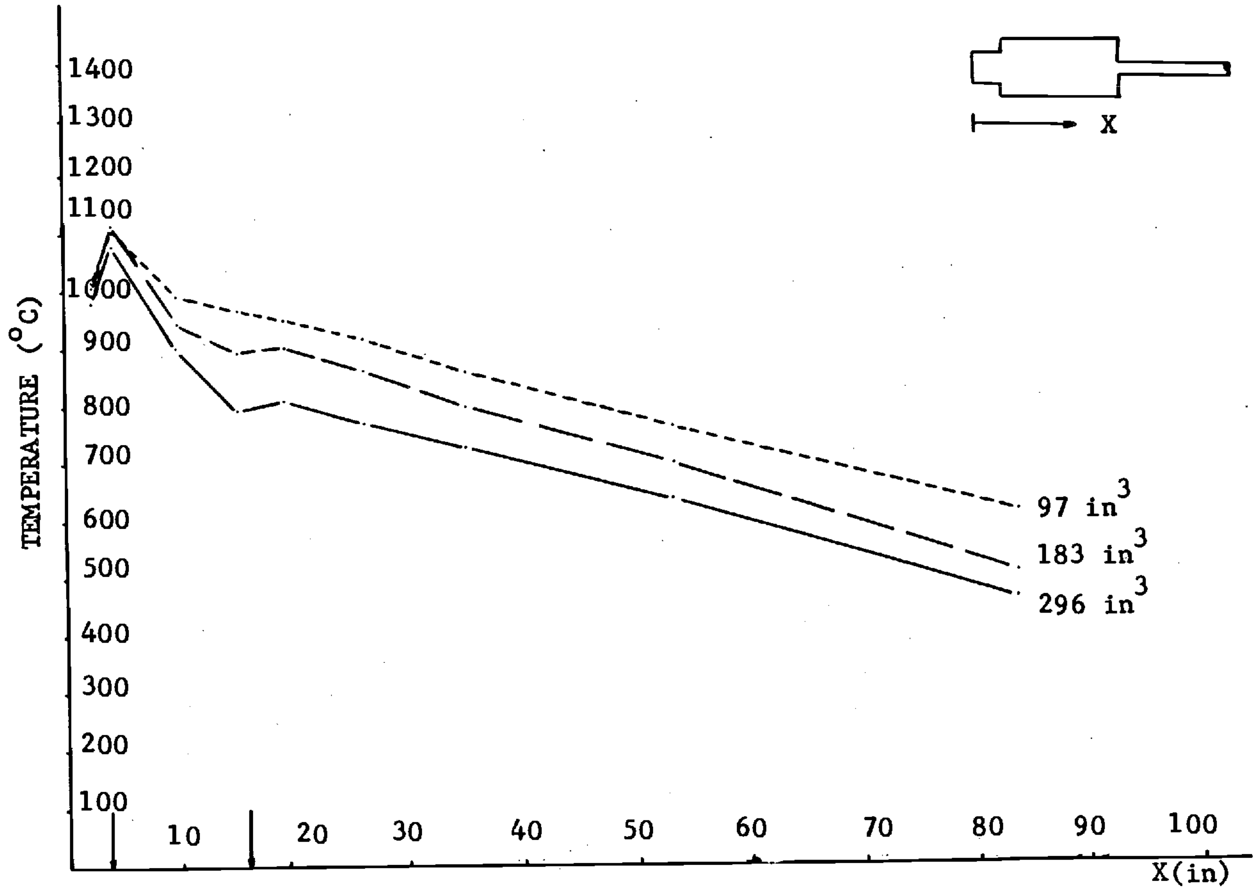


Figure 5. Mean Axial Temperatures vs. Axial Distance for Three Combustors of Three Different Volumes.

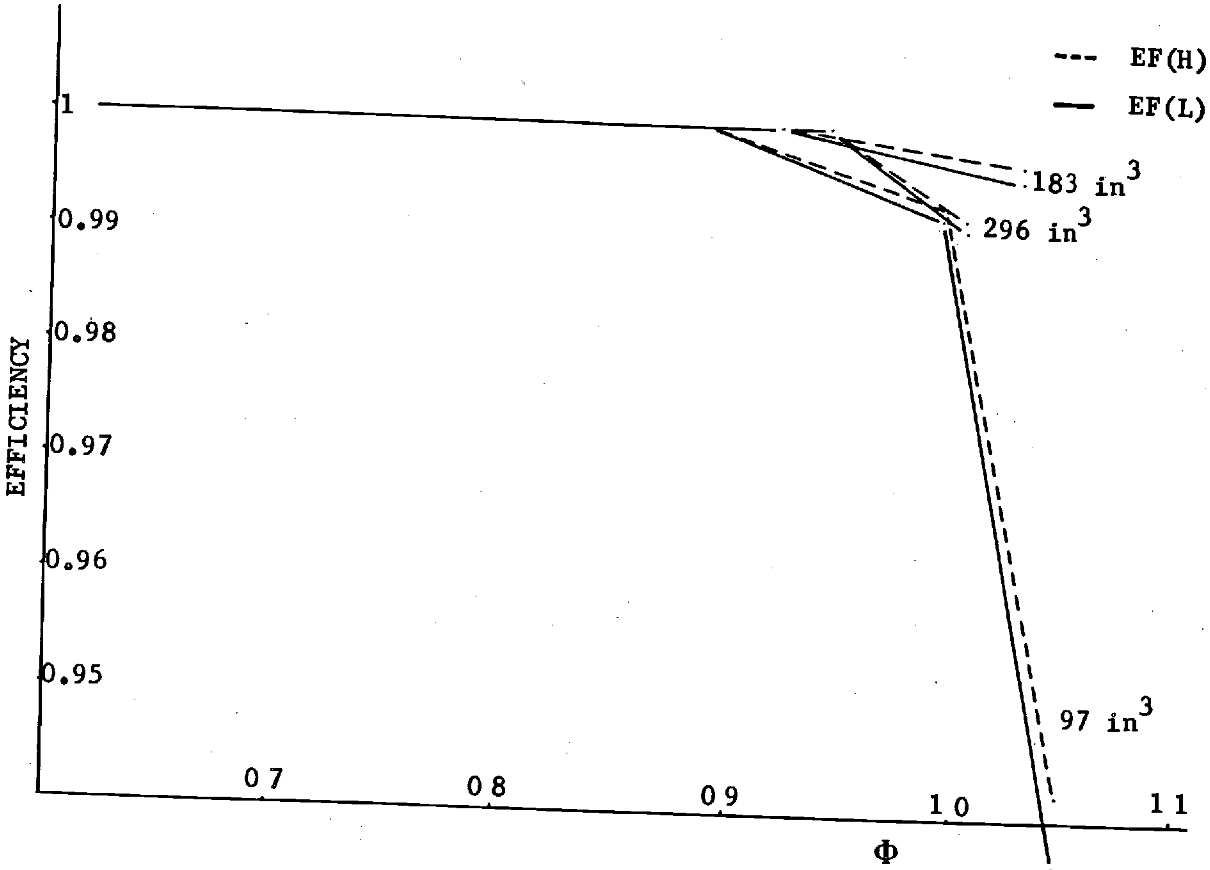


Figure 6. Efficiencies using High Heating Value (H) and Low Heating Value (L) of Methane vs. Fuel-Air Ratio for Combustors of Three Different Volumes.

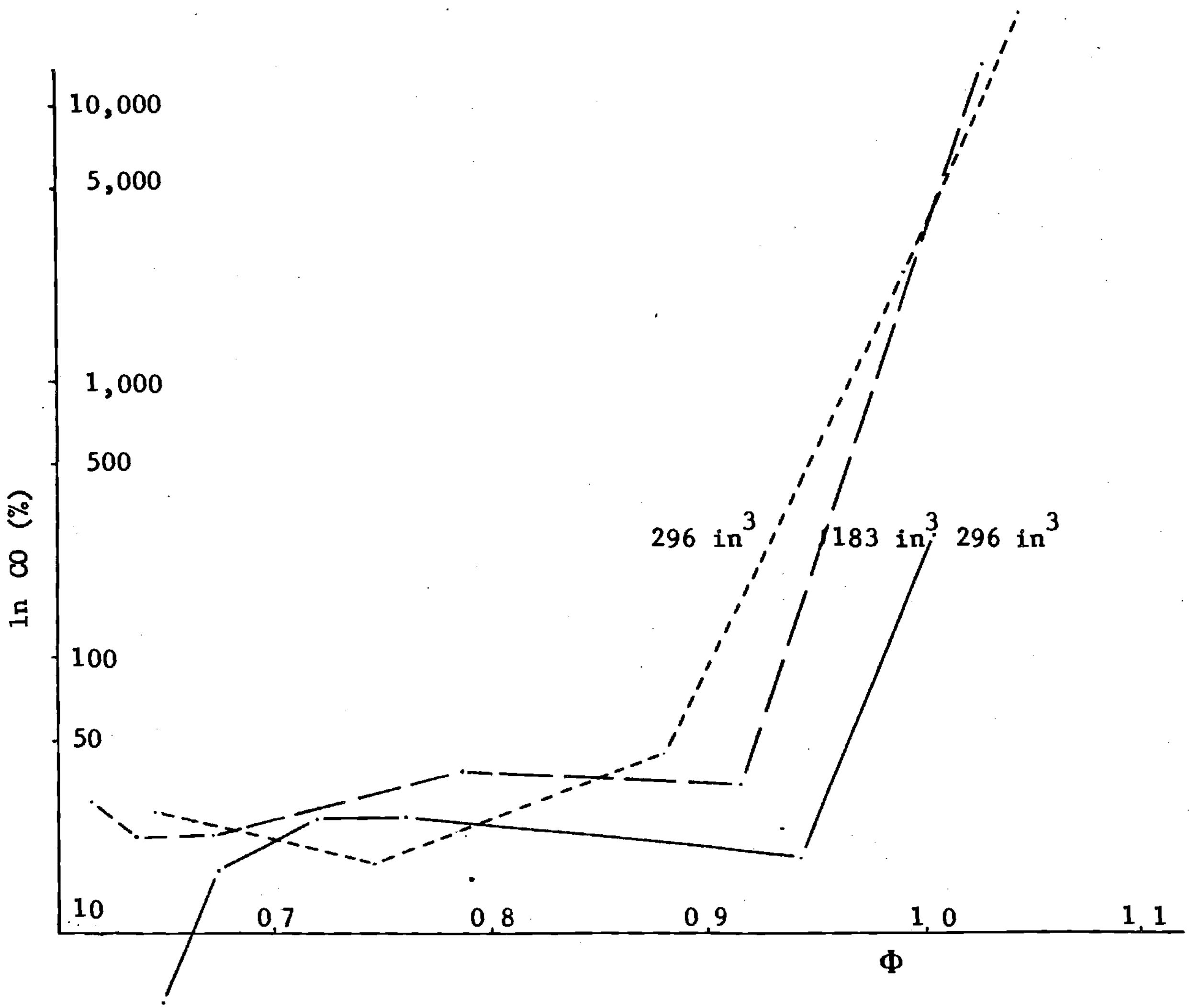


Figure 7. CO Concentrations vs. Fuel-Air Ratio for Combustors of 3 Different Volumes.

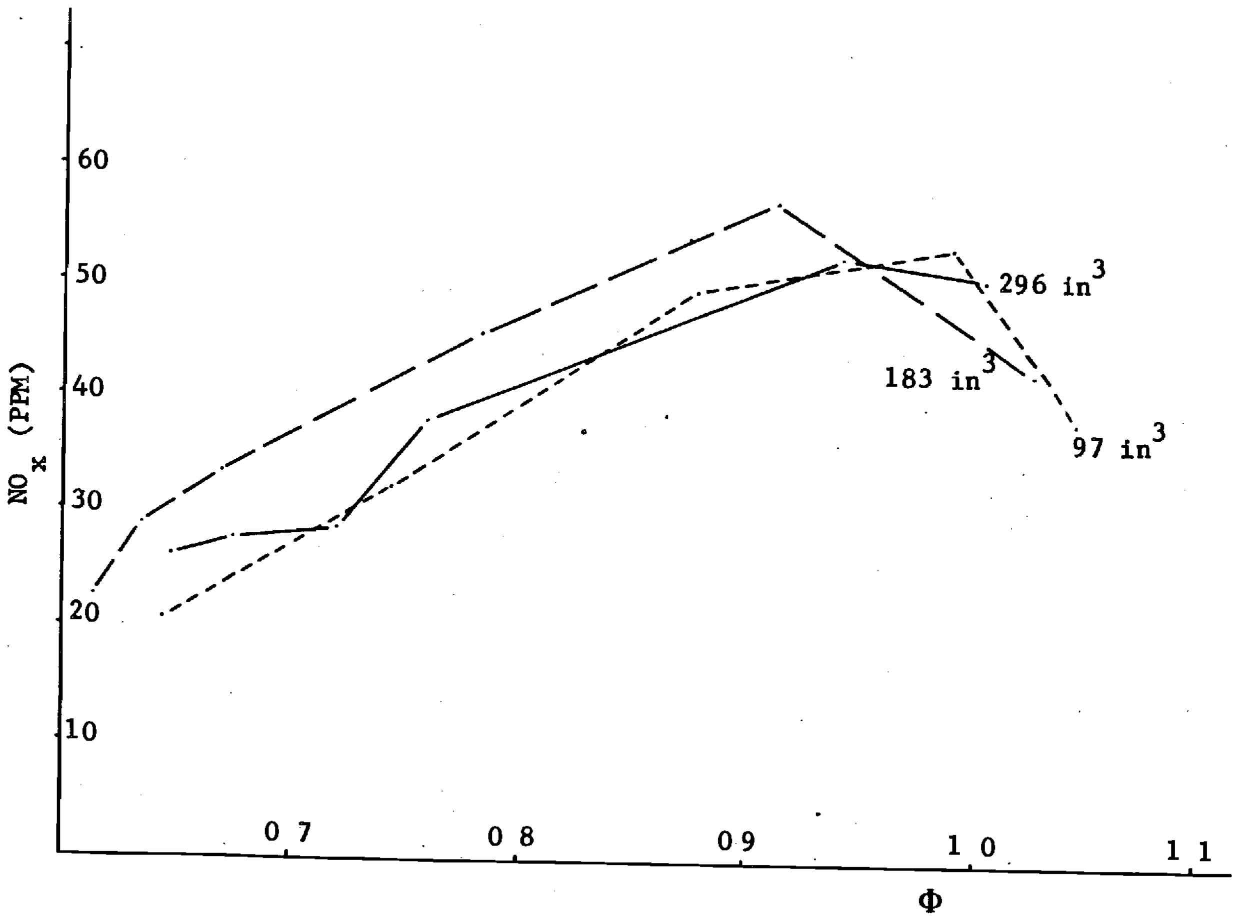


Figure 8. NO_x Concentrations vs. Fuel-Air Ratio for Combustors of Three Different Volumes.

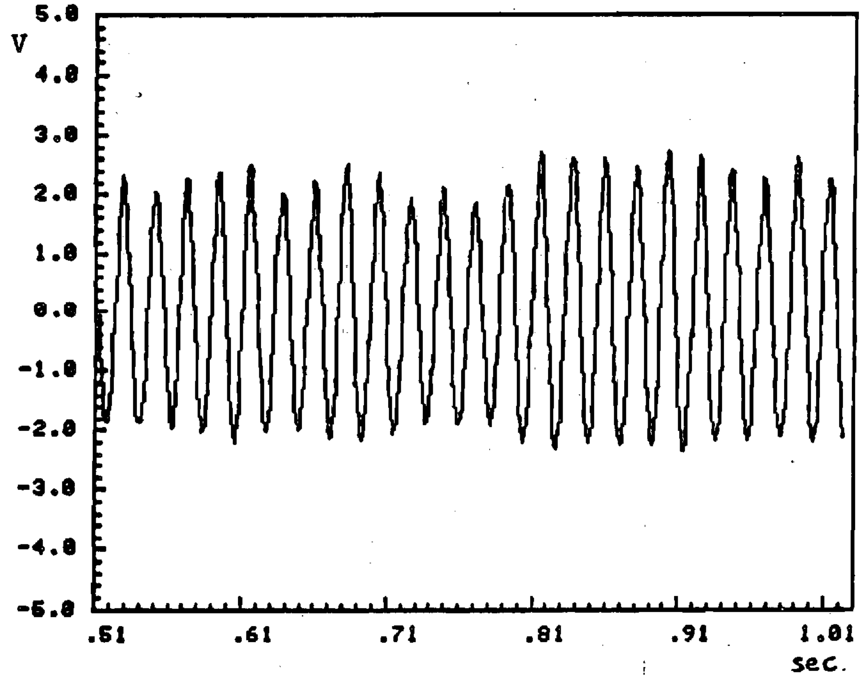


Figure 9. Representative Sample of Acoustic Pressure Oscillations in Pulse Combustor.

PULSATING BURNERS
CONTROLLING MECHANISMS AND PERFORMANCE

FINAL REPORT
(December 1983 - December 1986)

Gas Research Institute
8600 West Bryn Mawr Avenue
Chicago, Illinois 60631

Pulsating Burners - Controlling Mechanisms and Performance

Final Report

December 1, 1983 - December 31, 1986

Prepared by

B. T. Zinn, B. R. Daniel and J. I. Jagoda

School of Aerospace Engineering

Georgia Institute of Technology

For

Gas Research Institute

Grant No. 5083-260-0873

GRI/85-0032

GRI Project Manager

James A. Kezerle

Combustion

January 10, 1987

GRI DISCLAIMER

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO.	2.	3. Recipient's Accession No. GRI-8710220
4. Title and Subtitle Pulsating Burners - Controlling Mechanism and Performance			5. Report Date August 1987 (approved) 6.
7. Author(s) B. T. Zinn, B. R. Daniel and J. I. Jagoda			8. Performing Organization Rept. No.
9. Performing Organization Name and Address School of Aerospace Engineering Georgia Institute of Technology Atlanta, GA 30332			10. Project/Task/Work Unit No. E-16-662 11. Contract(C) or Grant(G) No. (C) 5083-266-0873 (G)
12. Sponsoring Organization Name and Address Gas Research Institute 8600 West Bryn Mawr Ave. Chicago, IL 60631			13. Type of Report & Period Covered Final Dec 1, 83 - Dec 31, 86 14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

The objective of this study is to gain an understanding of the physical and chemical processes which control the performance of gas fired pulse combustors. Performance measurements were carried out for combustors of different geometries. The chemical composition of the exhaust gases was measured and combustion efficiencies were calculated. The flow field in the combustor was visualized using high speed shadowgraphy. The location and timing of the heat release oscillations and their phase with the pressure fluctuations were determined by measuring acoustic pressures and radiation from OH radicals. The driving and damping characteristics of the combustor were determined by measuring growth and decay rates of the pressure oscillations. The combustor behaves like a Helmholtz resonator fitted with a long, open pipe. Its limits of operation are determined by the timing of the heat release in the pressure cycle. Fuel and air jets enter the mixing chamber, mix, and combustion proceeds, mostly in the mixing chamber, under conditions of intense, small scale turbulence. While combustion never completely stops, the location and timing of the new fuel charges in each cycle were determined. Driving and damping are dependent on the setting of the air flapper valve and on the geometry of the combustor.

17. Document Analysis a. Descriptors

Pulse Combustor

b. Identifiers/Open-Ended Terms Performance, Mixing, Reignition, Heat Release, Visualization, Radiation Measurements

c. COSATI Field/Group Combustion

18. Availability Statement: Distribution Unlimited	19. Security Class (This Report) Unclassified	21. No. of Pages
	20. Security Class (This Page) Unclassified	22. Price

(See ANSI-Z39.18) See Instructions on Reverse OPTIONAL FORM 272 (4-77) (Formerly NTIS-35) Department of Commerce

RESEARCH SUMMARY

<u>Title</u>	Pulsating Burners - Controlling Mechanisms and Performance
<u>Contractor</u>	Georgia Tech Research Institute
<u>Contract Number</u>	GRI Grant 5083-260-0873
<u>Report Period</u>	December 1, 1983 - December 31, 1987 Final Report
<u>Principal Investigator</u>	B. T. Zinn, B. R. Daniel and J. I. Jagoda
<u>Objective</u>	The objective of this study was to gain an understanding of the fundamental processes, such as mixing and cycle to cycle reignition, which control the operation of gas fired pulse combustors. An analytical model was to be developed to provide a rational procedure for the design and scaling of these burners.
<u>Technical Perspective</u>	In spite of the fact that gas fired pulse combustors for home heating have now been on the market for a number of years, little was known at the time when this project was initiated about the physical and chemical processes which control the operation of these devices. Of particular interest are the mixing of fuel and air, cycle to cycle ignition and the nature of the flame propagation in the burner. Such information is necessary for improving the operational characteristics of existing pulsating combustors and for guidance in the development of new burners for increased capacity or novel

applications. Furthermore, the acquired insight can be used to guide the development of a theoretical model for predicting the behavior of pulsating combustors. The availability of such a model would permit the replacement of the costly empirical trial and error methods used to date for the design and scaling of pulsed combustors by a more rational approach.

<u>Technical Approach</u>

A list of questions concerning the operation of pulse combustors was generated in order to focus the experiments on the most critical issues. The research was then directed to answer these questions.

As a first step, a parametric study was carried out using steel combustors in order to determine the influence of the combustor geometry, fuel/air ratio and air inlet pressure on their performance and efficiency. Burners were also fabricated of pyrex and quartz. Their flow fields were investigated using high speed Schlieren/shadowgraphy and stream line visualizations. A laser Doppler velocimetry (LDV) was readied for application. OH, CH and CC spectroscopy was used in determining of the timing, location and rate of heat release during the combustion cycle. The growth and decay of pressure amplitudes during start up and shut down were monitored to determine the driving and damping characteristics of the combustor. Some preliminary modelling efforts aimed at determining the best approach for modelling the pulse combustor behavior were performed.

Results

- The performance of the combustors was found to be independent of the length or diameter of the combustion chamber or of their ratio. However, the pulsation frequencies and their dB levels are inversely proportional to the combustion chamber volume. In addition, the frequency and dB levels varied inversely with the tail pipe length. It was thus determined that the pulse combustor behaves as a Helmholtz resonator whose neck was replaced by a long tail pipe.

- For the combustor operating at design load (i.e., 50,000 BTU/hr) the combustion process is almost entirely limited to the mixing chamber. The acoustic pressure near the end of the tail pipe is rugged and the acoustic energy is about 20 dB lower than in the combustor. The pressure oscillations in the mixing and combustion chamber are 180° out of phase with those in the exhaust pipe. The frequency of pulsations for any given combustor was found to be independent of fuel-air ratio while the dB level reached a maximum near stoichiometric operation.

- Combustion, which never stops entirely at any time during the cycle, takes place under conditions of intense, small scale turbulence. The combustion of the new charges in each cycle was found to occur later in the cycle the richer the equivalence ratio. Spacially resolved radiation measurements have shown that the ignition of the fresh fuel charges occurs in the region opposite the fuel inlet port from where the flame spreads through the mixing chamber. Near the rich limit a secondary ignition takes place near the center of the mixing chamber.

- Both damping and driving of the pulse combustor decreeases with an increase in the gap of the air valve. Also, both damping and driving are larger for the large and small combustors than for the intermediate size combustor.

Project Implications

This research, in conjunction with other GRI-sponsored research, has answered many critical questions about the operation of pulse combustors, as documented in this report and a companion report from Battelle. Furthermore, it was shown that the study of pulse combustors can be broken into two separate parts, combustion and system acoustics, which interface with each other through Rayleigh's criteria. Georgia Tech will characterize the acoustics of pulse combustion systems in a systematic way under a new contract. Data intended to explain scaling of pulse combustors are being collected on much larger combustors at Forbes Energy Engineering, Inc. Results from these two efforts need to be incorporated in a model in order to be useful to designers of pulse combustion equipment. It remains to be seen whether this will be completed at Georgia Tech or elsewhere.

GRI Project Manager

James A. Kezerle
Manager, Combustion
Physical Sciences Department

Table of Contents

I. INTRODUCTION

The objective of this study was to gain insight into the fundamental processes responsible for the operation of gas fired pulse combustors and to develop an analytical model capable of predicting the performance characteristics of new pulsed combustor designs. Furthermore, some of the theoretical efforts were expected to guide the development of new experiments and the interpretation of the measured data. To focus the program's efforts, a list of questions about pulse combustors was generated. The questions addressed by this research were:

1. What geometric parameters of a pulse combustor determine its performance such as frequency, dB level, combustion efficiency and pollutant emission?

2. What is the influence of the fuel air ratio upon the performance of the combustor? Are there any limits of operation and how could they be extended? What is responsible for these limits?

3. What are the acoustic conditions on the different parts of the pulse combustor?

4. What is the nature of the flow field and the resulting mixing pattern of the reactants and combustion products in the pulse combustor?

5. What is the phase between the pressure and the heat release fluctuations and how does it vary for different operating conditions of the pulse combustor?

6. Where and when does cycle to cycle reignition of the new reactants occur? Is there a single or are there multiple reignition sites? How does the flame spread through the pulse combustor?

7. What are the driving and damping characteristics of the pulse combustor under various operating conditions?

8. Can a model be developed that predicts the performance of a pulse combustor as a function of its geometry and operating conditions?

II. Program Plan

The program is divided into three major tasks as outlined below:

Task I -Experimental Investigations

A. Performance Evaluation. The performance of a number of combustors of different geometries (i.e., different L/D, volumes, tail pipe lengths, etc.) was investigated using temperature, pressure and combustion efficiency measurements. For each configuration, the performance was evaluated over a range of air/fuel ratios.

B. Flow Visualization. Stream lines were investigated by recording the tracks of seed particles moving through a laser light sheet. This process was repeated with the laser sheet at different combustor locations. Refractive index gradients caused by the flame front or by pockets of hot and cold gases were visualized using high speed Schlieren and shadowgraphy.

C. LDV. A 2-D Laser Doppler Velocimeter has been set up and tested, and is to be used to measure velocities at selected locations in the mixing and combustion chambers and in the tail pipe. Initial velocities to be measured will include the axial flow and swirl velocities in the mixing chamber and in the upstream part of the combustion chamber. These measurements will be carried out in a new combustor which has been fabricated with flat quartz windows in the cylindrical side walls of the mixing and combustion chambers. In addition, velocities will be measured in the plane in which the fuel and air jets enter the mixing chamber. These measurements will be made with the LDV in the back-scatter mode through the flat quartz window in the upstream end of the mixing chamber. The data acquisition system previously developed has been modified to permit ensemble averaging over a number of cycles.

D. OH, CH & CC Spectroscopy. In this part of the study radiation from the combustor was passed through appropriate filters and its intensity measured using a photomultiplier. These radiation intensities provide a measure of the combustion intensity. Measured global and spacially resolved radiation signals were correlated with measured pressure data and the timing of the reactant injection as determined from the high speed shadowgrams to determine the timing and location(s) of the initiation of the combustion process and its spread through the combustor.

E. Driving and Damping Studies. The acoustic driving and damping characteristics of various pulse combustor were determined by measuring the growth and decay rates of the pressure amplitudes during start up and shut down of these combustors.

Task II - Analytical Study

A simple theoretical model which provides the basis for the experimental determination of the acoustic damping and driving characteristics of pulse combustors has been developed. Furthermore, a theoretical model which describes the performance of the investigated combustors is being developed. The model will incorporate the findings of the experimental phases of the program. The model is non linear and it emphasizes the dependence of the combustor performance upon the flapper valve dynamics.

Task III - Reporting

As per contract agreement.

III. TECHNICAL APPROACH

Early in the project a test matrix for the parametric study of the performance of gas fired pulse combustors was developed, see Fig. 1. The eleven combustors described in this matrix were fabricated out of steel, including one in which the mixing and combustion chambers were of the same internal diameter. This eliminated the step between the two chambers. In addition three further combustors were fabricated which permit optical access to the mixing and combustion processes. One of these was entirely made of pyrex. Because the quality of the blown pyrex was not good enough to permit Schlieren measurement a second combustor was constructed. It consists of steel cylindrical walls with quartz discs fitted to the head of the mixing chamber and to the transition sections between the mixing and combustion chambers and the combustion chamber and tail pipe. Since this combustor limited optical access to the "end on" position, a third combustor with quartz end walls as well as flat quartz windows fitted to the cylindrical walls of the mixing and combustion chamber was constructed. A large decoupling chamber was added upstream of the air valve in order to be able to vary the air inlet pressure and to measure the air flow rate using a rotameter fitted upstream of the decoupler.

An exhaust gas sample train consisting of a heated sample line, a dryer, a CO_2 analyzer, a CO analyzer, an O_2 analyzer and a NO_x analyzer was set up to measure the exhaust gas compositions. A scheme was developed for determining the fuel-air ratios, combustion efficiencies and pollutant concentrations in the form of NO_x and CO in the exhaust gases from their chemical analysis. Software was written to acquire the data from the exhaust gas analyzers and to determine the above mentioned properties of the exhaust gas.

The combustors were fitted, throughout, (Fig. 2) with thermocouples and pressure transducers mounted in a semi-infinite tube configuration. Software was written to acquire, reduce, and display the temperature and pressure data in time series form, and to calculate the spectra of the pressure fluctuations and the phase angles between pressure traces at different locations in the combustor.

Optics were set up to measure the spontaneous radiation from OH, CH and CC radicals. Global radiation was measured by focusing the radiation from the entire combustor through the corresponding filter onto a photomultiplier tube. Spatially resolved radiation was measured using a long tube fitted with a series of apertures which eliminated all the radiation except that eminating from predetermined locations. Software was developed for the acquisition of the radiation data and the determination of their spectra and phase angles with respect to the pressure oscillations.

A high speed Schlieren system was adapted to the complex geometry of the pulse combustor, see Fig. 3. A 65 mwatt argon-ion laser was employed as a light source. In order to pass the expanded beam through the flat window between the combustion chamber and the tail pipe and through the end window of the mixing chamber, a diverging instead of a parallel beam had to be used in the test section. Nevertheless, good shadow images were obtained using this set up. In addition, a particle tracking system was set up. It consisted of a 5 watt Argon ion laser whose beam was expanded into a thin sheet by a cylindrical lens and passed through the all glass combustor. TiO_2 particles were injected into the combustor through the air flapper valve and their tracks through the laser sheet were recoded using a high speed camera at a framing rate of 6000 frames/sec. Finally, a two component LDV system was set up and tested. Software for the acquisition and reduction of LDV data including the ensemble averaging of the velocities at various instances throughout the pressure cycle, was written and tested.

IV RESULTS

A. Performance Evaluation

All eleven combustors were found to operate well and exhibited combustion efficiencies in excess of 99% as long as they were operated below stoichiometric conditions. This included the "stepless" combustor proving that the step between the mixing and combustion chambers is not needed in the investigated configuration for flame stabilization. The concentrations of NO_x and CO in the exhaust gases were determined to lie below 30 ppm and 50 ppm, respectively, except near the limits of operation of the combustor where the level of CO rises significantly. The operational frequency of the pulse combustor was found to be independent of its combustion chamber's length or diameter. However, both the frequency and the dB level of the combustor varied inversely with the combustor volume and the length of the tail pipe. It was, thus, determined that the pulse combustor behaves as a Helmholtz resonator attached to a long tail pipe instead of its usual short neck.

Mean temperatures measured along the combustor center line (Fig. 4) were seen to increase in the downstream direction in the mixing chamber and peaked just downstream of the junction between the mixing and combustion chambers. The mean temperatures then dropped quite rapidly in the downstream direction through the combustion chamber and the tail pipe, indicating the presence of high heat losses to the walls under pulsating conditions. The location of the maximum centerline temperature along with visual observations of the combustion process in the all-pyrex combustor indicate that, for this combustor operating under design load (50,000 BTU/hr), the combustion was almost entirely confined to the mixing chamber.

Acoustic pressures were measured in the mixing and combustion chambers, in the tail pipe, and in the fuel line between the fuel valve and the mixing chamber. The pressure fluctuations everywhere except near the end of the tail pipe were sinusoidal, with most of the acoustic energy concentrated in the fundamental mode (Fig. 5). The frequencies were found to be constant while the amplitudes exhibited small fluctuations. In contrast, the acoustic pressure spectrum near the end of the tail pipe is more rugged and the amplitude drops by about 20 dB. The pressure oscillations in the mixing and combustion chambers are 180^{o} out of phase with those in the exhaust pipe. Furthermore, the pressure oscillations in the mixing chamber slightly lead those in the fuel line, see Fig. 6. This results in a somewhat higher pressure in the fuel line than in the mixing chamber early in the cycle. Fuel or combustion products from the fuel port thus enter the mixing chamber before the pressure in the mixing chamber falls below the fuel supply pressure. This behavior was confirmed by observations using the high speed Schlieren system as discussed later. Finally, the frequency of pulsations for a given combustor was found to be independent of equivalence ratio while the dB level reached a maximum near stoichiometric conditions, as expected, since stoichiometric combustion results in the highest heat release per unit mass of reactants.

The range of stable operation of the standard AGA combustor was determined to be between $\phi \sim .6$ and $\phi \sim 1$. These limits could not be significantly extended by insulating the combustor either externally or internally, although the latter caused a significant reduction in both the frequency and the dB level. The dB drop was primarily due to the acoustic damping by the liners used for thermal insulation. It was, however, possible to considerably extend the rich limit of operation by either supplying the combustion air under pressure or by extending the tail pipe and, thus, the duration of the pulse cycle.

B. Flow Visualization

"End on" high speed shadowgraphy was carried out on the AGA standard combustor with quartz flat end walls. The resulting records clearly show a jet of cold gas entering the mixing chamber through a fuel port before the pressure in the mixing chamber falls below the fuel supply pressure as explained above. The air jet follows the fuel jet resulting in swirl-induced mixing. Vortices are seen to shed off the leading edges of both reactant jets. The timing during the cycle at which the reactants are injected into the mixing chamber varies significantly between normal operations and near the limits of operation (Table 1). Combustion is seen to take place under conditions of intense, small scale turbulence. The reaction is nearly complete prior to injection of the new fuel for the next cycle except near the rich limit of operation where fuel injection for the next cycle was observed to take place while significant combustion was still going on in the mixing chamber.

Particle tracking and mixing visualizations, using the expanded laser sheet passed through the all pyrex combustor, were hampered significantly by the fact that a considerable amount of light was lost from the laser sheet. These losses were due to reflection from the curved combustor walls through which the sheet had to pass. This resulted in a much reduced intensity of the light scattered by the seed particles as they passed through the test section. The resulting particle tracks were not very clear. Nevertheless, the air jet entering the mixture chamber and the swirling motion of the gases were clearly visible. However, no additional information over and above that resulting from the Schlieren visualization was obtained. A new combustor has recently been fabricated which has flat quartz windows fitted to the cylinderical side walls of the mixing and combustion chambers. This combustor should provide better capabilities for illumination in the mixing chamber and, thus, clearer particle track and mixing records.

C. Laser Doppler Velocimetry

A new combustor in which flat quartz windows were fitted into the cylindrical walls of the mixing and combustion chambers has been designed and fabricated. This avoids the problem of the displacement of the LDV beams due to the cylindrical side walls in the all-quartz combustor. Software has been developed which permits the ensemble averaging of the velocity data over many cycles. For this purpose the period of pulsations has been divided into 36 equal time segments. LDV counts for each segment will be stored in separate files. Mean velocities and turbulence intensities as well as shear stresses can then be obtained for each instant in the cycle.

D. Spectropic Studies

Measurements of OH, CH and CC radiation were carried out simultaneously with pressure measurements in the combustor to determine the phase between the heat release and pressure oscillations. The global radiation measurements showed that the radiation and, therefore, the combustion process does not stop at any instant during the cycle. Furthermore, it was observed that CC emissions lead those of CH and OH except near the rich limit where the order is reversed (Table 2). Also, the ignition of new charges in each cycle occurs earlier in the cycle the lower the fuel equivalence ratio. This behavior is due to the fact that when operating under fuel lean conditions, air from the previous cycle is available for combustion with the entering fuel charge. However, as stoichiometric conditions are approached no oxygen from the previous cycle is available and the fuel mixing and combustion await the later arrival of the air jet. In the rich limit, there is then not enough time left for complete combustion of the fuel during the period of the oscillations, whose length is largely determined by the dimensions of the combustor. It is, thus, no coincidence that the rich limit of operation for the AGA standard combustor occurs near stoichiometric conditions. As reported earlier, this rich limit can be extended, however, by prolonging the duration of the cycle (using a longer tail pipe) or by causing earlier injection of the air and improving mixing (through pressurizing the air supply).

Spacially resolved radiation measurements permitted the determination of the location of cycle to cycle reignition of the fresh fuel charge and the flame spread through the combustor. Fig. 7 shows lines of constant phase angle between the OH radiation and the pressure oscillations near the middle, lean and rich limits of operation. The numbers indicate the phase angle by which the radiation leads the pressure. The higher the phase the earlier combustion occurs at the indicated location. In all three cases the new charges ignite in the mixing chamber opposite the fuel port. From the ignition spot the flame front spreads through the mixing chamber. Near the rich limit a secondary ignition zone is observed near the center of the mixing chamber where the air jet first impinges upon the fuel jet. Closer inspection of the lean limit case shows (Fig. 8) that the early part of the combustion cycle occurs more than 90° out of phase with the pressure. The dB level of the radiation fluctuations is shown on the left hand side of Fig. 8. Comparison of the two parts of Fig. 8 indicates that the part of the combustion cycle which is out of phase with the pressure fluctuations exhibits large radiation oscillations. A considerable fraction of the heat release per cycle is, thus, out of phase with the pressure and damps rather than drives the pulsations. The limits of operation of the pulse combustor are, thus, caused by the timing of the combustion process in the cycle. At the lean limit combustion occurs too early and, therefore, damps the oscillations because Rayleigh's criteria are no longer satisfied. Near the rich limit, on the other hand, Rayleigh's criteria are satisfied. However, combustion commences too late to be completed within the duration of the cycle. In addition, the fact that near the lean limit some of the combustion heat release damps the oscillations helps to explain the observed drop off in dB level which occurs near the lean limit of operation of the combustor.

E. Driving and Damping Studies

The driving and damping characteristics of the pulse combustor were determined by measuring the exponential growth and decay rates of the pressure oscillations during start-up and shut-down of the combustor. A simple model of the transient behavior of the combustor, developed during the course of this study, shows that the growth rate of the oscillations during the combustor start-up is proportional to the difference between the combustion process' driving and the system's damping processes. On the other hand, the decay rate of the pressure amplitude during the combustor shut down phase, after the fuel flow has been stopped is a measure of the system's damping only.

Since the normal starting procedure of the pulse combustor involves the firing of an ignition spark which interferes with the measurement of the pressure signals, the combustor is started using a minimal amount of fuel provided by a small fuel line which bypasses a fast acting solenoid valve. This valve is then opened suddenly and the resulting sudden increase in the fuel input causes an exponential growth of the pressure amplitude which is recorded (Fig. 9).

To measure the decay rate of the combustor pressure, the valve is shut and the decay of the amplitude is recorded. However, after shutting the valve some fuel is left in the line between the valve and the fuel injection port in the mixing chamber. Limited driving, due to the presence of this fuel, continues for a number of additional cycles. Spontaneous OH radiation along with the pressure decay rate were measured to determine the instant (i.e., cycle) at which the combustion and, therefore, the heat release had completely stopped. The damping coefficient was calculated from the pressure amplitude decay rate which occurred after that instant (Fig. 10).

Due to the low frequency of the pulsations the needed growth and decay rates coefficients were determined from measurements of amplitude variations during a few cycles. Since this provided only a few points for each growth or decay test, a large number of tests had to be run and the data averaged to obtain reasonable data. The measured data show (Table 3) that for a given combustor the driving (i.e., α_{dr}) increases and the damping (i.e., α_{d2}) decreases as the air valve spacing is increased. Additional tests have shown that both the driving and damping depend upon the combustor volume. Measurements of driving and damping characteristics as a function of system geometry will continue under the new contract.

F. Analytical Study

A simple model, which treats the combustor as a Helmholtz resonator-like volume attached to a long, open tube, was found to very accurately predict the natural frequency of the combustor under cold flow conditions. A similar model was used to predict the frequency of the pulsations under combustion conditions. In this approach a mean temperature was used in each of the combustor components to determine a mean speed of sound. Using this model in combination with an empirical factor, which was determined experimentally for a given combustor configuration, the frequencies of all other configurations could be predicted with good accuracy.

The goal of the more detailed theoretical studies was to develop a model capable of determining the dependence of the combustor performance, expressed in terms of the pulsation amplitude and frequency, the steady state pressure, limits of operation and so on, upon the combustor operating conditions and configuration. Special attention was to be paid to the dependence of the pulse combustor performance upon the configurations and settings of the flapper valves, and the factors which control the characteristics of the steady state pressure field within the pulse combustor. To attain this goal, work towards the development of a nonlinear model of the pulse combustor behavior was initiated. After considering both the physical and mathematical aspects of the problem it was decided to obtain the needed solutions by use of a perturbation solution technique.

To obtain these solutions, the pulse combustor flow was divided into several regions; that is, the flapper valves, the mixing chamber, the combustor and the tail pipe. Next, the conservation equations which describe the behavior of the pulsations, up to second order in the pulsation amplitude, were derived and the mathematical structure of the expected solutions was determined. In addition, considerable work was expended on the analysis of the flapper valve dynamics. Unfortunately, the Ph.D student working on this task had to leave school and return to work and we are currently waiting to hear whether he will be able to continue this work in absentia. If this does not turn out to be the case, other options for continuing the work at Georgia Tech will be pursued.

V. CONCLUSIONS

The work carried out under this contract helped to shed new light on the operational characteristics of gas fired pulse combustors. Answers to the specific questions listed in the introduction were determined to be as follows:

1. The important geometric parameters of the pulse combustor are the combustion chamber volume and the tail pipe length. The combustor behaved, essentially, like a Helmholtz resonator attached to a long, open pipe.The combustor frequency and dB level, thus, decreased with increasing chamber volume and tailpipe length. The combustion efficiency and the emission level of CO and NO_X were found to be largely independent of combustor geometry. The step between the mixing and combustion chambers has no influence upon the performance of the combustor.

2. The standard pulse combustor operates well for fuel-air ratios between 0.6 and one when the air is supplied to its flapper valve at atmospheric

pressure. The rich limit of operation can be extended by increasing the air supply pressure or by lengthening the duration of the pressure cycle through extending the tail pipe. These limits of operation of the pulse combustor are caused by the timing of the combustion process in the pressure cycle. At the lean limit combustion occurs too early in the cycle. The resulting heat release is then out of phase with the pressure oscillations which according to Rayleigh's criteria causes the pressure oscillations to be damped. Near the rich limit heat release and pressure oscillations are in phase. However, no air is left from the previous cycle which delays the reignition of the new fuel charge until air from the new cycle enters the mixing chamber. Insufficient time is then left to complete combustion during the cycle unless air is injected earlier by pressurizing the air supply or the duration of the cycle is extended. Furthermore, as the fuel-air ratio is increased the frequency of the pulse combustor remains constant while the dB level increases slightly. This results in an increase in the fuel flow rate for a fixed fuel flapper valve setting.

3. The pressure oscillations in the mixing and combustion chambers and in the upstream part of the tailpipe are sinosoidal. The oscillations in the tailpipe are 180 degrees out of phase with those in the chambers. Near the end of the tailpipe the pressure fluctuations become more rugged and their amplitude drops by 20 dB. Pressure oscillations in the fuel line slightly lag those in the mixing chamber causing new fuel to enter the mixing chamber before its pressure falls below the pressure in the fuel line.

4. In each cycle a narrow, high speed jet of fuel enters the mixing chamber followed by a wider, slower air jet. The interaction between the two jets results in a swirling flow field in which combustion occurs under conditions of intense, small scale turbulence. Except near the rich limit, combustion is almost completed before the reactants for the next cycle enter the mixing chamber.

5. The oscillations in heat release always lead those in pressure. As the fuel-air ratio is increased the heat release and pressure oscillations become more and more in phase.The relative timing between the heat release and the

pressure fluctuations are responsible for the lean and rich operating limits as discussed in paragraph 2.

6. The combustion process in the pulse combustor operating at design load is, essentially, limited to the mixing chamber. Combustion never completely ceases at any time during the cycle. Ignition of the new fuel in each cycle occurs in the mixing chamber opposite the fuel port for all combustor operating conditions. Near the rich limit a secondary ignition zone occurs near the center of the mixing chamber where the fuel and air jets first mix. From the ignition spots the flame spreads throughout the mixing chamber.

7. For a given combustor the driving increases and the damping decreases as the air valve spacing is increased. Also, both damping and driving are larger for the small and the large combustors than for the intermediate sized device.

8. The natural frequency of the combustor can be predicted for cold flow conditions if the combustor is modelled as a Helmholtz resonator fitted with a long, open tube. Similarly, the frequency of pulsations can be predicted under combustion conditions if the measured mean temperature is used to evaluate the mean speed of sound. The detailed model of the individual components which make up the pulse combustor was not completed during this contract period.

VI. RECOMMENDATIONS

In order to fully understand the operation of the gas fired pulse combustor, additional information must be obtained on the details of the velocity field, the mixing and the heat release mechanism in this combustor. In addition, the impedance of the various subsystems which make up the pulse combustor must be determined. Furthermore, the effect of the combustor geometry upon the damping and driving characteristics of the pulse combustor must be measured. Finally, the development of a model capable of predicting the combustor performance from its geometry and its operating conditions should be continued.

In particular, the following experimental work should be carried out:

1. Velocities should be measured at selected locations in the combustor using the laser Doppler velocimeter. Particular attention should be paid to the flow field in the highly turbulent region in which the jets of fuel and air first mix. The velocities in the axial direction must be measured in order to determine the extent of the back flow during each part of the cycle. In addition, the importance of swirl in the mixing and combustion chambers must be established.

2. The flow field in the axial direction of the combustor should be visualized using high speed shadowgraphy. These shadowgrams should then be correlated with those previously obtained through the window in the end of the mixing chamber in order to obtain a complete picture of the three dimensional flow field in the pulse combustor.

3. The mixing visualization studies should be repeated using the combustor with flat windows fitted into the curved side walls of the mixing chamber. The optical quality, flat windows would considerably reduce the amount of laser light lost and, thus, significantly improve the quality of the images obtained.

4. Global and local heat release rates should be determined by measuring the OH, CH and CC radical radiation through the side window in the mixing and combustion chambers. These measurements should then be correlated with those previously obtained through the window in the end of the mixing chamber.

5. Local densities and, therefore, temperatures in the pulse combustor should be measured using Rayleigh scattering. This will yield a quantitative description of the path taken by the hot combustion products during the different parts of the cycle.

6. The acoustic impedance of the various components and subsystems which make up the pulse combustor should be measured using the impedance tube technique. These measurements should be carried out without and with combustion for a range of driving frequencies. This will yield information on

the frequency dependance of the damping provided by the subsystems which make up the combustor. In addition, the frequency dependance of the driving provided by the pulse combustion process can be determined.

7. The overall damping and driving characteristics of pulse combustors of various geometries should be determined by measuring the growth and decay rates of the combustor pressure oscillations during the start-up and shut-down phases of combustor operation.

8. The detailed analytical model capable of predicting the pulse combustor performance from the combustor's geometry and operating conditions should be completed.

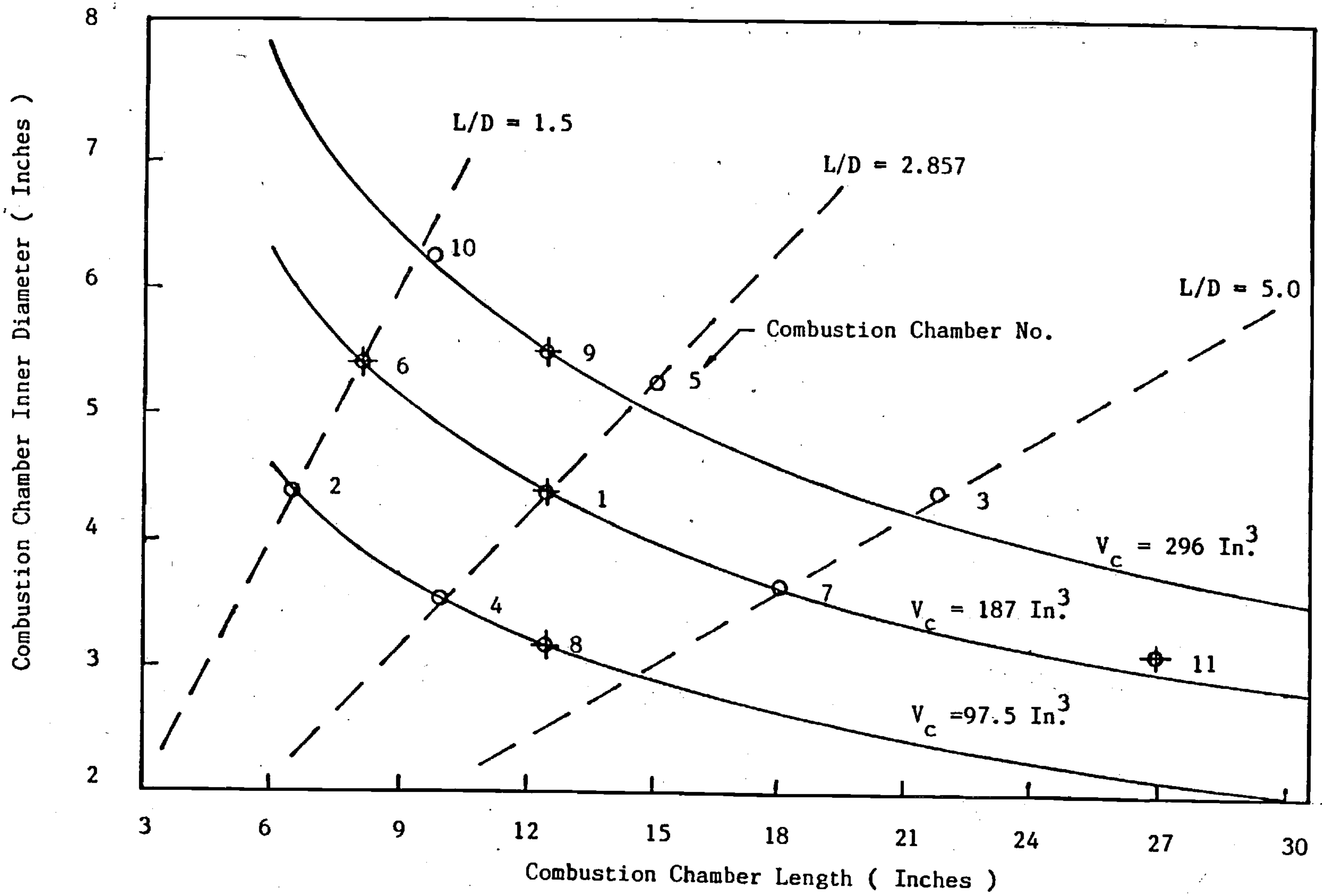


Fig. 1. The Distribution of Combustion Chamber Geometry Parameters

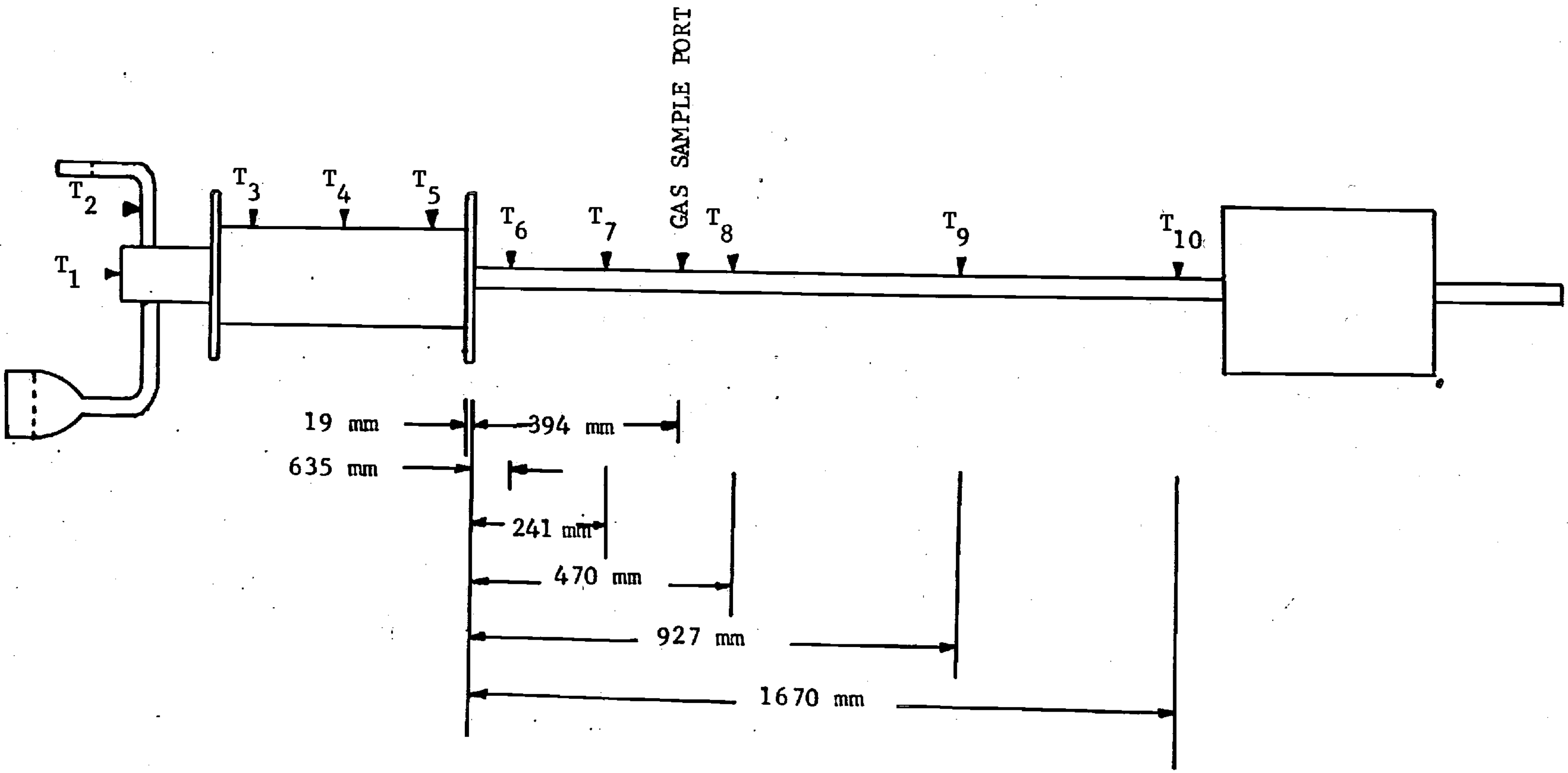


FIGURE 2. LOCATION OF MEASURING STATIONS.

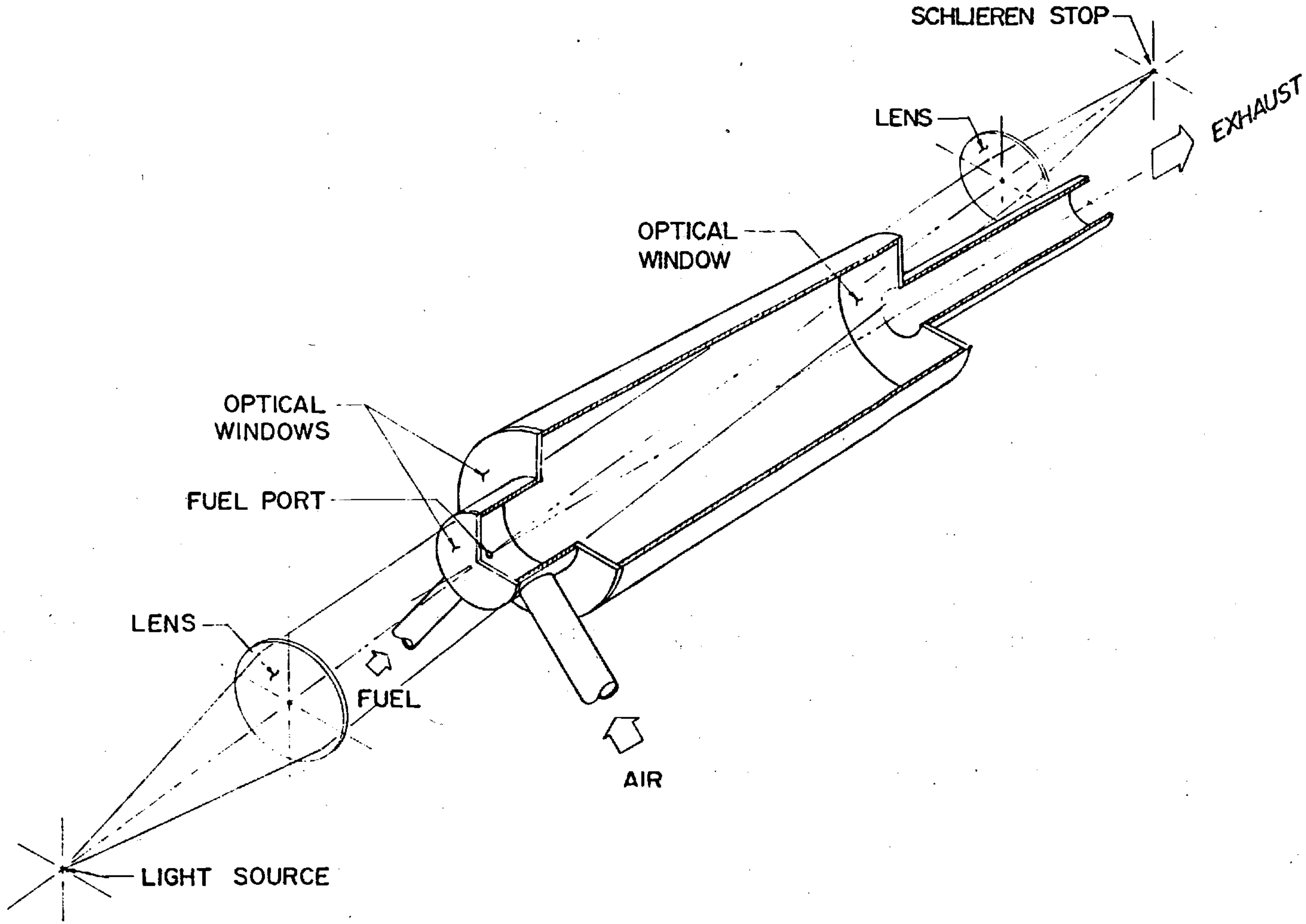


Fig. 3. Schlieren Set-up.

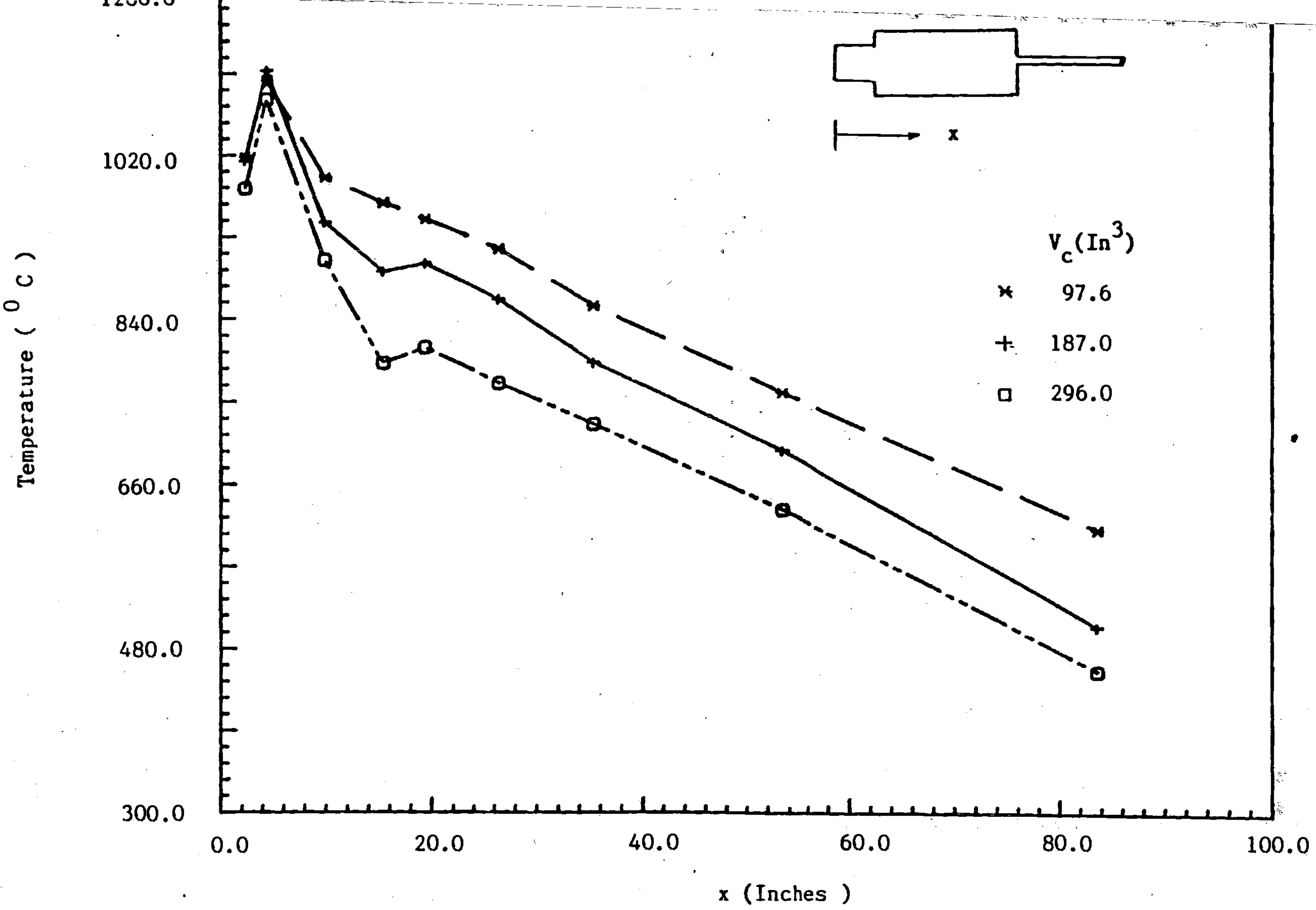


Fig. 4 . Temperature Distribution for Three Combustors of Different Volume

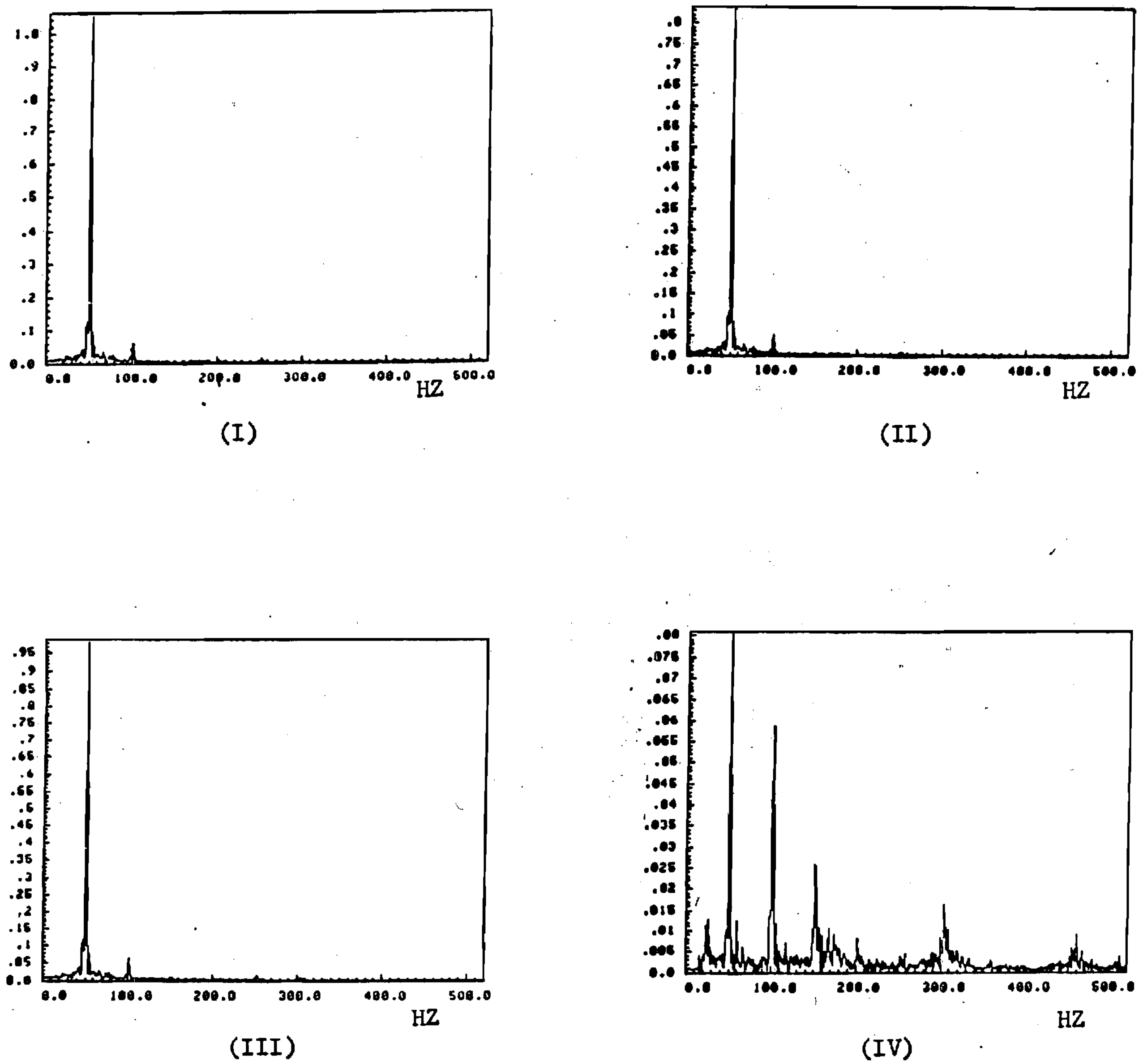


Figure 5. Acoustic Pressure Spectra for Optimum Fuel/Air Ratio. (I) in Mixing Chamber, (II) in Combustion Chamber, (III) at the Head of Exhaust Pipe, (IV) at the Exit of Exhaust Pipe.

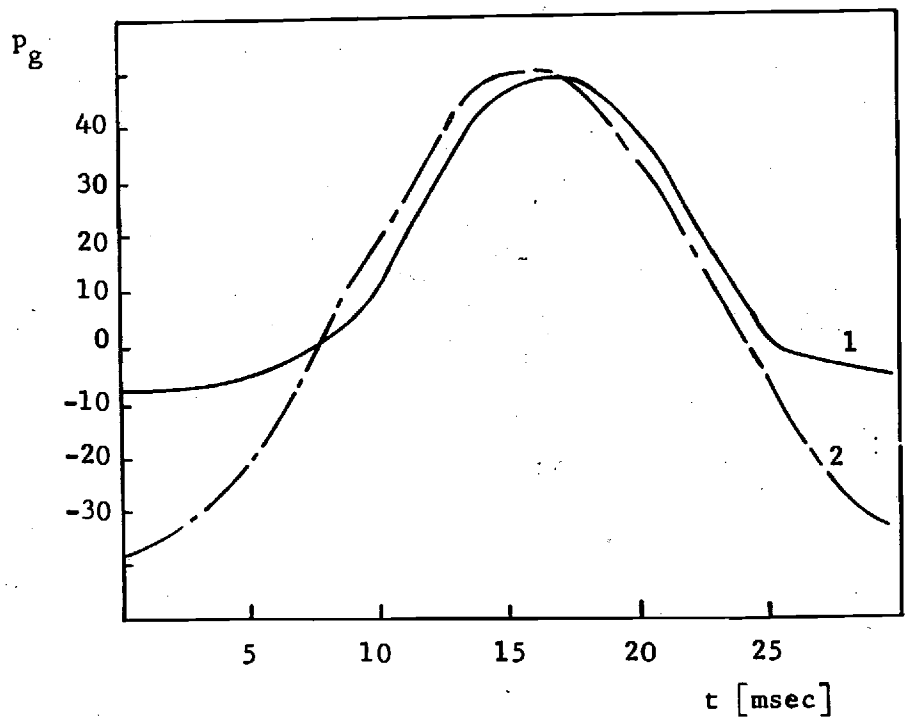


Fig. 6. PRESSURE FLUCTUATIONS IN 1) FUEL LINE, 2) COMBUSTOR

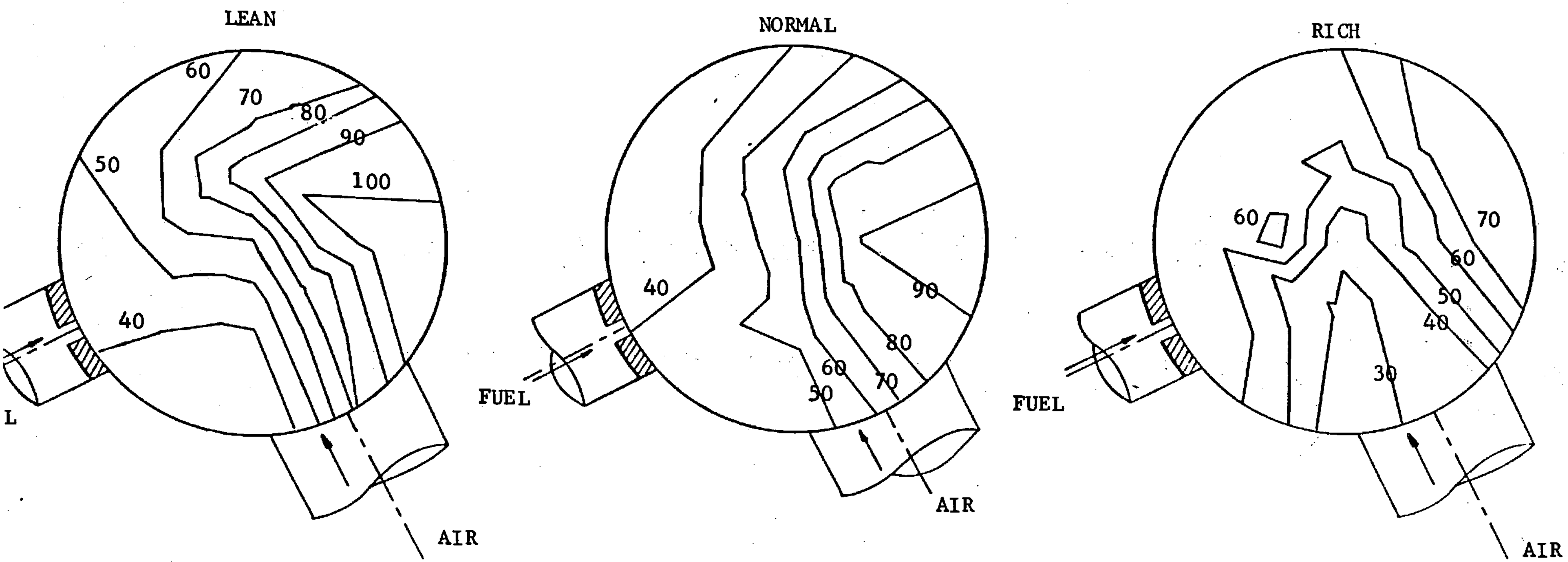


Fig. 7. SPACIALLY RESOLVED OH RADIATION MEASUREMENTS
PHASE ANGLE BY WHICH RADIATION LEADS PRESSURE

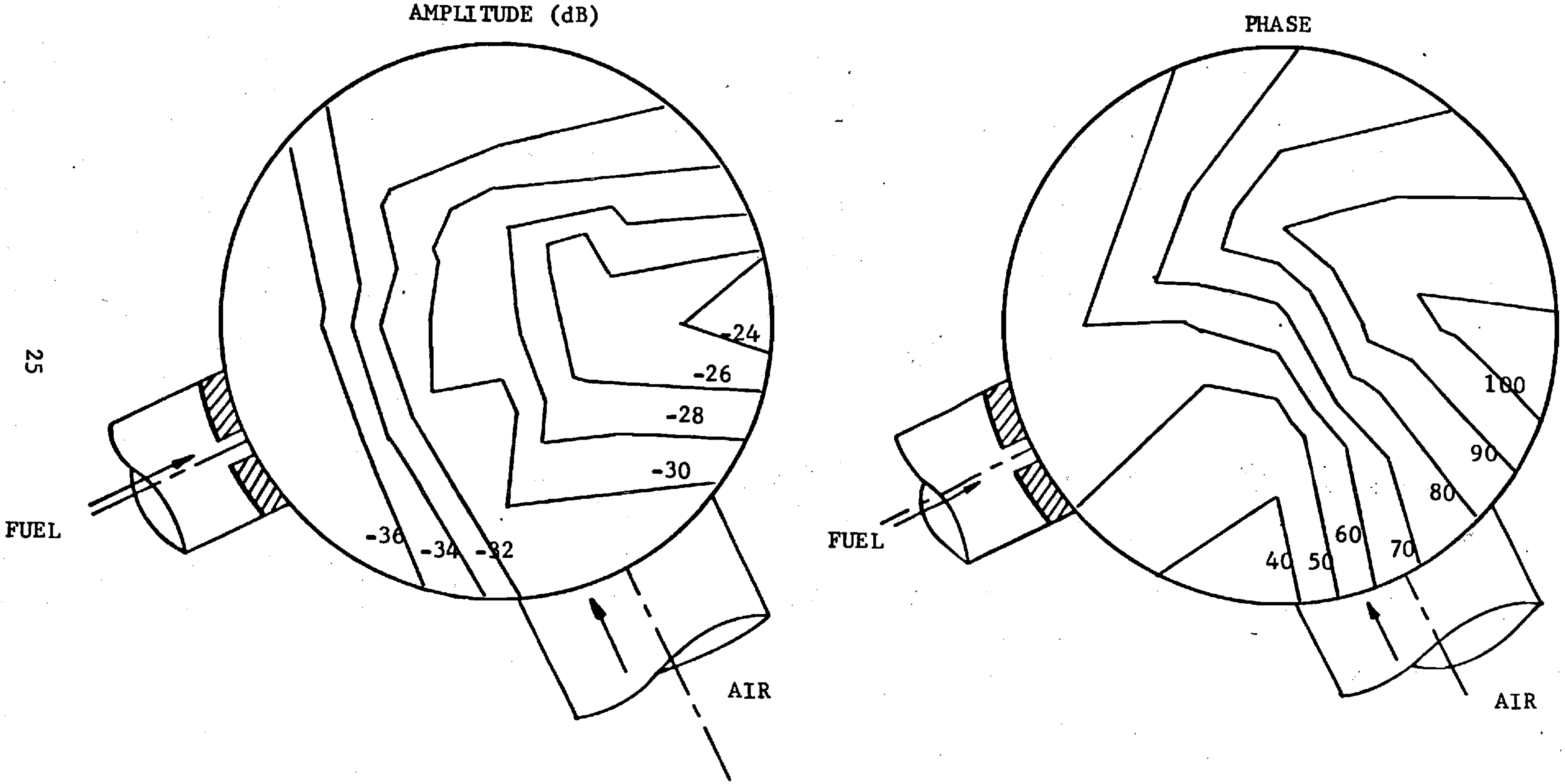


Fig. 8. SPACIALLY RESOLVED CC RADIATION MEASUREMENTS
FOR LEAN CONDITIONS, AMPLITUDE AND PHASE

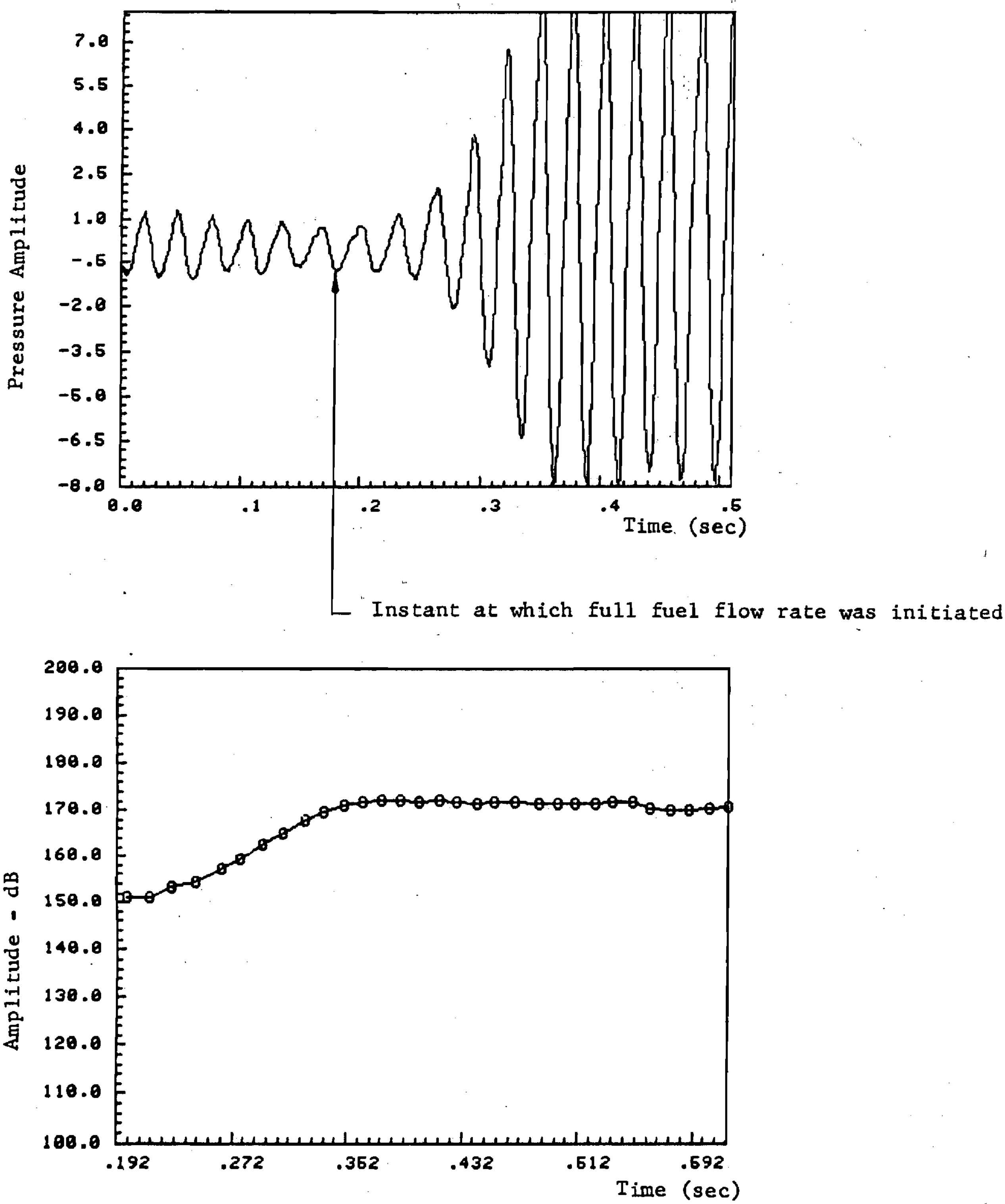


Fig. 9. Time Dependences of the Combustor Pressure and dB Level during Combustor Start Up Phase for Combustor No. 1 and 0.012" Air Valve Opening.

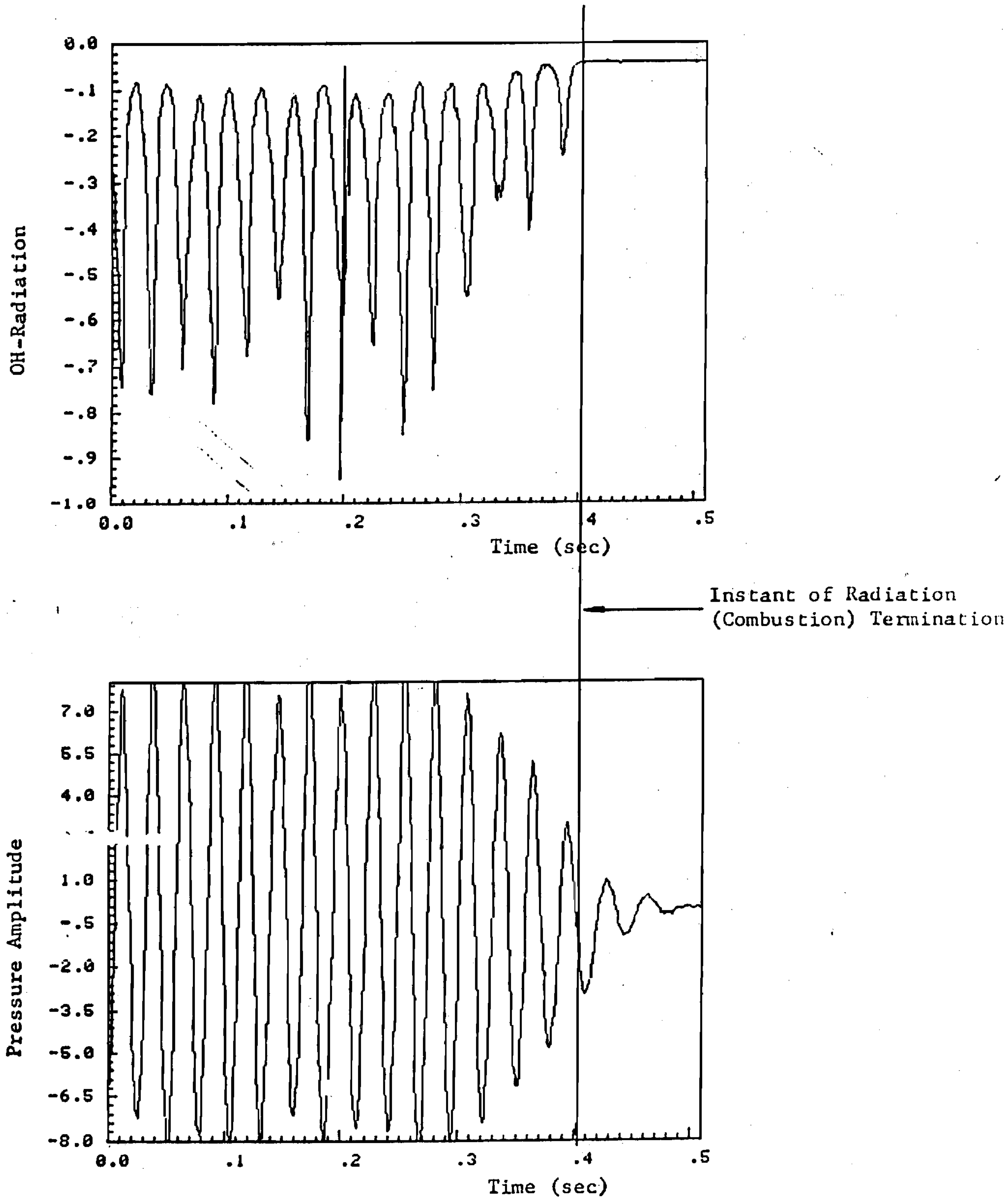


Fig. 10. Time Dependences of the Combustor Pressure and OH-Radiation during Combustor Shut Down Phase for Combustor No. 1 and .009" Air Valve Opening.

Table 1.

TIMING (IN MSEC) OF VARIOUS EVENTS IN THE CYCLE FOR THE COMBUSTOR OPERATING WITH DIFFERENT FUEL/AIR RATIOS.

	Fuel jet enters	Air jet enters	Air jet impinges on fuel jet	Complete cycle
Lean limit	0	1.55	3.35	25.18
Normal	0	3.5	6.0	23.75
Rich limit	0	6.9	9.2	28.80

Table 3.

DRIVING/DAMPING CHARACTERISTICS OF AGA COMBUSTOR:

AIR VALVE OPENINGS

	.009" RICH	.012" NORMAL	.015" LEAN
α_{d_1}	-22.5	-26.5	-32.4
α_{d_2}	-52.3	-45.3	-33.2
α_a	69.2	70.5	66.8
$\alpha_{dr} = \alpha_{d_2} + \alpha_a$	17.2	25.2	33.6

(1) BEFORE COMPLETE FUEL BURN OUT

(2) AFTER COMPLETE FUEL BURN OUT